

RESEARCH ARTICLE

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Key Points:

- Ho Chi Minh City's flood damage may increase beyond 1 order of magnitude in the next decades due to sea level rise and growth
- Several adaptation measures could effectively be applied and yield high economic returns on investment
- Analysis of adaptation pathways shows that combining measures over time can effectively reduce damage and risk to human lives

Supporting Information:

- Supporting Information S1
- Table S1

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Adaptation to Sea Level Rise: A Multidisciplinary Analysis for Ho Chi Minh City, Vietnam

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Abstract One of the most critical impacts of sea level rise is that flooding suffered by ever larger settlements in tropical deltas will increase. Here we look at Ho Chi Minh City, Vietnam, and quantify the threats that coastal floods pose to safety and to the economy. For this, we produce flood maps through hydrodynamic modeling and, by combining these with data sets of exposure and vulnerability, we estimate two indicators of risk: the damage to assets and the number of potential casualties. We simulate current and future (2050 and 2100) flood risk using IPCC scenarios of sea level rise and socioeconomic change. We find that annual damage may grow by more than 1 order of magnitude, and potential casualties may grow 5–20-fold until the end of the century, in the absence of adaptation. Impacts depend strongly on the climate and socioeconomic scenarios considered. Next, we simulate the implementation of adaptation measures and calculate their effectiveness in reducing impacts. We find that a ring dike would protect the inner city but increase risk in more rural districts, whereas elevating areas at risk and dryproofing buildings will reduce impacts to the city as a whole. Most measures perform well from an economic standpoint. Combinations of measures seem to be the optimal solution and may address potential equity conflicts. Based on our results, we design possible adaptation pathways for Ho Chi Minh City for the coming decades; these can inform policy-making and strategic thinking.

Plain Language Summary While sea levels gradually rise, concerns about coastal floods become higher, especially in low-lying cities in the tropics. In Ho Chi Minh City, Vietnam, floods are already large and frequent. Here we look at how coastal floods, and their impacts, will evolve on this city during the coming decades. Using different scenarios of sea level rise and socioeconomic growth, we calculate that risk, in terms of urban damage and potential casualties, may increase even more than 10-fold, if adaptation measures are not taken. We then simulate the realization of different adaptation measures: a ring dike, elevating part of the city, retrofitting buildings, and changing land use, and their combination. Most measures have the potential of reducing a considerable part of flood risk. The ring dike has the disadvantage that it would protect the inner city while increasing risk in outer districts; if implemented, it should therefore be combined with other measures. Also, the economic performance of most measures seems highly positive, suggesting that adaptation will generate high returns on investment. We conclude our analysis by generating possible adaptation pathways, to inform decisions on the type and timing of adaptation in Ho Chi Minh City.

1. Introduction

The potential increase in flood intensity and probability is among the most severe impacts that climate change poses to delta cities (Hunt & Watkiss, 2011; Wong et al., 2014). This is most relevant for the tropics, where the combined effects of sea level rise (SLR) and of a fast-growing population and economy pose a challenge to the livability of densely inhabited cities of low-lying deltas (McGranahan et al., 2007).

Low latitudes will likely face maximum SLR relative to the global mean and are projected to undergo more intense hydrological stress due to the effects of warming on the monsoon systems (IPCC, 2013). SLR is perhaps the most concerning consequence of climate change for tropical delta cities, since it is more certain in comparison with other changes and implies a virtually permanent shift in the hydraulic and hydrological dynamics of coastal areas.

It has been shown that the threat from coastal flooding will grow with SLR (Vitousek et al., 2017). The integration of different disciplinary approaches is necessary to understand the implications for urban coastal systems (e.g., Xu et al., 2016).

Regarding responses to increasing threat, the need to improve adaptation planning has long been recognized (Füssel, 2007). Yet actual assessment of the effectiveness of specific adaptation measures (e.g., Budiyono et al., 2017; de Bruin et al., 2009) and of their costs and benefits (Aerts et al., 2014) are not yet frequent in the literature. From the perspective of decision-making in adaptation, the scope of analysis has been expanded to include consideration of the “deep” uncertainty inherent in climate projections, such as through the application of adaptation pathways (Barnett et al., 2014; Ranger et al., 2013).

Yet the multiple aspects that are key to understanding impacts and adaptation of coastal cities to SLR are typically studied separately, yielding a fragmented picture of the broad problem to decision-makers. To address this gap, we proposed here a framework that encompasses climate and socioeconomic scenario analysis, hydrodynamic modeling, estimation of economic damages and of potential casualties, quantitative assessment of the effectiveness and economic performance of adaptation measures, and analysis of adaptation pathways.

We quantify the impacts of SLR and of socioeconomic growth on Ho Chi Minh City, which lies on the Saigon Delta and close to the Mekong Delta, and investigate the possibilities of reducing such impacts through adaptation.

1.1. Present and Future Floods in Ho Chi Minh City

Ho Chi Minh City (hereafter HCMC) is one of the rapidly growing metropolises in Southeast Asia. It is the most populated city of Vietnam, hosting 9% of the population, and much of the industry and commerce of the country, generating about 21% of the country's GDP. Also, it is a major maritime hub in the region. However, flooding occurs annually in HCMC, often due to a combination of heavy rainfall, discharge from upstream reservoirs, and storm surges coinciding with high tide. This phenomenon is tied to the summer monsoon, when the easterlies discharge moisture from the East Sea, implying even higher water levels in extended areas, and stalling the drainage valves system of the city (Moens et al., 2013). This causes economic damage and nuisance to daily life and business, and considerable intangible losses due to traffic congestion. The number of people and the values of assets exposed to coastal flooding are among the highest in the world (Hanson et al., 2011).

In recent years, a number of projects have directed their focus to the issues arising in HCMC due to flood stress (e.g., Asian Development Bank, 2010; Dahm et al., 2013; FIM, 2013a; Ho et al., 2014, 2015; Webster & McElwee, 2009; World Bank, 2010). Regarding the future, projections of SLR in the HCMC region are slightly higher than the global mean (IPCC, 2013; Jevrejeva et al., 2014). Notwithstanding, projections of the local impacts of climate change are still not univocal, with global climate models indicating either increase or decrease in the frequency of large floods (Arnell & Gosling, 2016). A recent study has focused on a densely populated central district of HCMC and used flood and damage models to obtain annual losses in year 2050, with socioeconomic changes and 30 cm of SLR (Lasage et al., 2014). It was reported that climate change impacts outweigh socioeconomic developments in determining flood risk.

In response to pluvial flooding, HCMC's storm sewer system is presently undergoing upgrading by a number of projects under the framework of the Japan International Cooperation Agency; these projects are about halfway to completion (Ho et al., 2015). But further action on flood protection is urgently needed, as shown again by the floods of October 2016, caused by the combination of seasonal high tide and heavy rainfall (VnExpress.net, 2016). Recently, several measures to reduce flood risk have been discussed: building a ring dike, to protect either the whole city (the “MARD plan,” developed by the Ministry of Agriculture and Rural Development) or only the urban part of the city west of the Saigon river (the “MARD plan variant”); and placing a tidal barrier at the Saigon river's mouth, thus protecting the whole HCMC (FIM, 2013b; Ho et al., 2015).

Besides the lack of financial resources, the evident delay in implementation of measures in HCMC may be due in part to the lack of a comprehensive study of impacts and of the effectiveness of possible measures. In fact, although many sources indicate that climate and socioeconomic drivers will likely increase impacts of floods, the future changes in risk have received little attention yet. As a result, decision-makers perceive a

situation of excessive uncertainty regarding future risk, and especially regarding the outcomes of any risk-reducing measures they could take.

In this study, we hydrodynamically simulate floods in HCMC and calculate risk for the present and for two time horizons in the future: around year 2050 and year 2100. For the future, we account for climate-driven changes, namely sea level rise, and for socioeconomic changes, namely in demography and the economy. To address the fundamental uncertainties that city management is faced with when adapting to climate change (Aerts & Botzen, 2014), we simulate different scenarios for the future, factoring in both SLR and socioeconomic change. Then, based on the impacts we obtain, we devise and implement a range of adaptation measures in the hydrodynamic and impact simulations; then we recalculate the impacts, assuming that these measures are realized.

Our aims are as follows:

1. To conduct the first structured and integrated assessment of the risk posed by floods to people and assets in HCMC, under present conditions and under different scenarios of the future.
2. To understand the relative contribution of socioeconomic growth and of SLR to the future change in flood risk.
3. To quantify the effectiveness of several adaptation measures aimed at reducing flood risk and to evaluate their economic performance and social suitability.
4. To combine adaptation measures into adaptation pathways for the coming decades.

With this analysis, we aim to provide authorities in HCMC with science-based projections of future flood risk, and thereby improve risk-management decisions. We show that the performance of different adaptation measures varies in the amount of damage and casualties they can prevent, and in their social acceptability. Via cost-benefit analysis, we suggest that structural and building-scale measures against flood are highly rational from an economic perspective, and we provide a pressing case for investments into adaptation.

2. Methods

We adopt a framework that encompasses climate projections, flood and impact modeling, and risk estimation, as schematized in Figure 1. Briefly, floods are simulated using a hydrodynamic model, taking extreme values of precipitation, river discharge, and sea level, and including projections of sea level rise. Further, in the impact modeling phase, flood depth is used as an input to a damage model, in conjunction with vulnerability curves, land use maps, and projections of socioeconomic change, to obtain direct floods losses. Flood depth and flow velocity are processed by a casualty model to estimate the number of people in life-threatening situations. Finally, the direct losses and the potential casualties for floods associated with four return-periods are translated into expected annual impacts, our indicators of flood risk. Adaptation measures are accounted for in the framework by modifying the hydrodynamic modeling, the vulnerability curves and the land use maps. Lastly, we carry out a cost-benefit analysis of the adaptation measures; and we generated potential adaptation pathways for the future of HCMC. These models and data sets are described next and in the supporting information.

2.1. Flood Modeling

The hydrodynamic regimes in the river basins of HCMC are simulated using the TELEMAC 2D model (Hervouet, 2000). The spatial resolution varies across the domain between 50 and 100 m for the river bed mesh and between 100 and 500 m for the terrain mesh. The temporal resolution is 20 s. Different types of land cover (urban, river, and agriculture) are included by changing the Chézy coefficient over the model domain. We focus on storm surges from the East Sea and simulated these events at return-periods of 1, 10, 100, and 1,000 year, based on present-day observations. Additional boundary conditions included are peak discharges and peak rainfall. Regional studies suggest that climate-change-induced changes in precipitation extremes will not exceed a few percentage points (Ministry of Natural Resources and Environment (MoNRE), 2009). Hence, we applied uniform values for peak rainfall (5 year return-period) and for peak discharge (10 year return-period) across all flood simulations. Given a lack of empirical information on the probability of compounded riverine, pluvial, and coastal floods (Dahm et al., 2013), these are considered plausible approximations of meteorological and riverine conditions in the wide range of return-periods of storm surge. Land

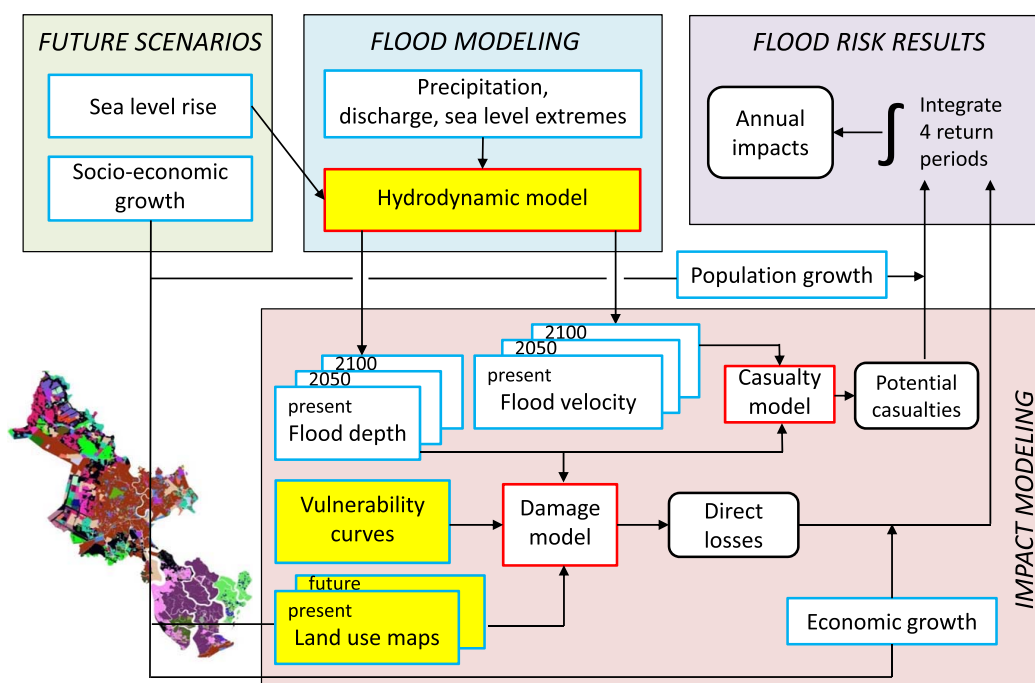


Figure 1. Flowchart of the methods. Models are in red boxes and results are in rounded boxes. Yellow boxes indicate the points in the modeling where adaptation measures are implemented. Data sets of future scenarios, where socioeconomic and climate pressures are included, are used as input to flood and impact modeling. The results of the impact modeling for four return-periods are then expressed as risk: i.e., annual damage and potential annual casualties.

subsidence due to groundwater extraction and compaction affects potential flood depths in HCMC (Dang et al., 2014; Trung & Dinh, 2009). Because reliable spatially explicit information on this effect is lacking, land subsidence is not considered in our modeling approach. In the simulations, we assume the capacity of urban drainage systems to be overloaded by intense rainfall and high tide, so that water runoff takes place on the streets of HCMC. Further details of the modeling set up are included in the supporting information. Details of the model calibration and validation are contained in Nguyen et al. (2013). The outcomes of the flood modeling are flood maps, representing flood depth in HCMC at 10 m horizontal resolution.

2.2. Socioeconomic Impact Modeling

We quantify the socioeconomic impacts of flooding with the indicators: direct damage to buildings and their content (expressed in US\$); and potential casualties (number of people facing life-threatening situations).

2.2.1. Damage Model

For the assessment of direct economic damage inflicted on assets in HCMC, we use the Damage Scanner model (Klijn et al., 2007), which has been applied in approaches similar to ours (e.g., Koks et al., 2015; Lasage et al., 2014). The inputs are flood maps obtained as described in section 2.1; land use maps; economic value at stake per unit of area; and depth-damage curves for each land use (reported in supporting information Figure S3). The latter specify the proportion of a land use-specific economic value that is lost for any given flood depth. The damage associated with a given flood is calculated for each cell by multiplying the land use-specific maximum value by the land use-specific damage factor that is associated with the local flood depth. To calculate annual damage, flood maps with different return-periods are used to represent a range of possible magnitudes of the event (Ward et al., 2011). Damages related to each of these flood events are weighted according to their probability of occurrence in any year, which yields the average annual damage that can be expected.

2.2.2. Casualty Model

To project changes in the direct threat that floods pose to the lives of citizens of HCMC, we apply a method developed in the SUFRI project of the Crue Era-Net (Diaz-Loaiza et al., 2012; Jobstl et al., 2011). The method calculates potential casualties over the flooded streets, distinguishing classes of water depths and water

velocities per grid cell. Because death by flood is a highly complex phenomenon that still eludes realistic representation by algorithms, the results of our casualties estimation should be considered as the statistical number of people that may face life-threatening situations during the flood. Because of this, and because to the best of our knowledge, reliable historical estimates of flood casualties in HCMC are not available, we focus on the relative changes in potential casualties across simulations rather than on the absolute numbers.

2.3. Future Scenarios

We simulate flooding for the present and for two future time horizons: year 2050 and year 2100. We take climate change into account through projections of SLR and changes in the socioeconomic situation through projections of GDP growth (Table 1). For climate change, we use data from models that apply two IPCC emission scenarios, Representative Concentration Pathway (RCP) 4.5 and RCP8.5 (Moss et al., 2010). For socioeconomic change, we use the recent Shared Socioeconomic Pathway (SSP) scenarios (Riahi et al., 2016), developed for the IPCC reports. We select SSP scenarios whose narratives are compatible with that of the selected RCP scenarios, specifically the following combinations:

- RCP4.5 and SSP2: moderately optimistic with respect to the capacity of society to mitigate greenhouse gasses, with stabilization of concentrations in the second half of this century;
- RCP8.5 and SSP5: rapid and integrated economic growth, but business-as-usual practices in greenhouse gas emissions, leading to increasing atmospheric concentrations along this century.

2.3.1. Sea Level Rise Projections

For SLR in RCP4.5 and RCP8.5, we use the central values estimated from an ensemble of process-based models of SLR, presented in Jevrejeva et al. (2014), specific for the region of the South China Sea nearest HCMC, which are slightly higher than the global mean (Table 1). Also, to contemplate the high-end of possible outcomes, we use SLR values at the 95th percentile of the high emission scenario RCP8.5 (henceforth named "RCP8.5 High-end"), from the same study. We therefore have three SLR scenarios: RCP4.5, RCP8.5, and RCP8.5 High-end.

The SLR projection used by the Vietnamese government (MoNRE, 2009) is 100 cm for year 2100 (with respect to the 1980–1999 average), which derives from the IPCC A1F1 emission scenario (IPCC, 2007). This falls between the RCP8.5 and RCP8.5 High-end projections we use here, so our results are relevant to policy development by Vietnamese authorities.

2.3.2. Socioeconomic Projections

We account for socioeconomic development by incorporating projections of GDP and demographic growth.

For GDP, we apply growth rates obtained from Integrated Assessment Models that apply the SSP narratives. These are available from the work of two different teams at the International Institute for Applied Systems Analysis (IIASA) and the Organization for Economic Co-operation and Development (OECD). Growth rates

Table 1
Summary of Information Adopted for Each Scenario

		Year 2050			Year 2100		
		RCP4.5	RCP8.5	RCP8.5 High-end	RCP4.5	RCP8.5	RCP8.5 High-end
Climate scenarios	Present						
Sea level rise (cm)	0	23	23 ^a	49 ^a	49	64	180
Socioeconomic scenarios		SSP2	SSP5	SSP5	SSP2	SSP5	SSP5
for GDP growth							
Population density	Year 2015	+41%	+41%	+41%	+41%	+41%	+41%

Note. Sea level rise projections are from Jevrejeva et al. (2014); socioeconomic projections after SSP scenarios are from IIASA and OECD, available at the SSP Public Database website (<https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about>); population density projections are our average of different available data sources (see section 2.3).

^aJevrejeva et al. (2014) specify central value estimates of regional sea level rise of 29 cm for scenario RCP8.5 and of 52 cm for scenario RCP8.5 High-end in year 2050. To reduce the amount of calculations, we considered these values to be reasonably close to 23 and 49 cm, respectively, applied in other scenarios, and therefore used the results of these simulations.

are specific for Vietnam and evolve at 10 year time steps until 2100. We apply the average of the growth rates generated by the two teams (see supporting information Figure S4).

To account for demographic growth, i.e., variations in the exposed population across the city, we use available projections. For HCMC, the population is projected to grow, from 2010 to 2025, by either 36% (HCMC Master Plan: DPA, 2010) or 46% (Demographia data are available at <http://www.demographia.com/db-wuaproject.pdf>). After year 2025, demographic stabilization is expected for Vietnam (World Bank, 2014). Therefore, for all future scenarios, we take an average increase in the HCMC population of 41%, assuming long-term stabilization at about 10.5 million people.

2.4. Adaptation Measures

In the following, we provide a description of the adaptation measures and their combinations, with reasons and details about their inclusion in the simulations. The details of how we calculate the approximated costs of realization and of maintenance (where applicable) of each measure, for the cost-benefit analysis, are reported in supporting information (section 1.2).

2.4.1. Business-As-Usual

A number of sparse dikes and levees exist in HCMC, but they do not form a coherent and effective protection against floods. The urban drainage system is being upgraded but is in general poorly maintained (FIM, 2013a). We assume that these structures are maintained at their current levels of effectiveness. This situation serves as the benchmark against which adaptation performance is measured.

2.4.2. Ring Dike

A ring dike is modeled that encircles the inner part of HCMC, where more population and economic activities are located (Figure 2). This, together with a more peripheral ring road, corresponds to a ministerial adaptation plan known as “MARD Variant,” which is presently undergoing technical evaluation (FIM, 2013b; Ministry of Agriculture and Rural Development of Vietnam, 2013). We simulate the impacts of a ring dike that is 30 cm higher than the water table during a present-day 100 year flood event (as recommended by the Vietnamese government; Ministry of Construction, 2008), i.e., on average 230 cm above the current mean sea level. This is implemented in the hydrodynamic model by modifying the land elevation input data set.

2.4.3. Elevation

With the ongoing replacement of buildings in the reurbanization of HCMC, it is already observed that new buildings are being constructed at a higher elevation than the surrounding older buildings (Lasage et al., 2014), by raising the ground level with sand. We model the elevation of entire areas of HCMC that are most densely populated and thus likely undergo the highest damages in a typical flood event (Figure 2)—corresponding to about 180 km²—by modifying the land elevation data set used in the hydrodynamic model. We assume elevation takes place over 10 years and corresponds to 30 cm higher than the present-day 100 year flood, yielding a total elevation of 230 cm above the current mean sea level.

2.4.4. Dryproofing Buildings

We simulate impacts of dryproofing residential houses and small businesses, i.e., making buildings watertight until 1 m of flood depth. This measure is particularly interesting because of its scalability, low cost, and relatively fast implementation.

2.4.5. Land Use Change

In contrast to the land use map from the year 2010, to simulate changes in land use, we employed a land use map of the Master Plan for year 2025 (DPA, 2010). This map reflects the view of the local and central governments about the urban evolution of HCMC. This plan does not explicitly aim to minimize flooding risk from SLR.

2.4.6. Combination of Measures

We also simulate the impacts of combinations of measures: ring dike + dryproofing buildings; elevation + dryproofing buildings.

For each measure, we estimated the approximated cost of realization and maintenance (where applicable), using data from the literature. These are reported in supporting information Table S3.

2.5. Cost-Benefit Analysis

The adaptation measures above are economically evaluated through cost-benefit analysis. The reduction in expected damage represents the benefit of adaptation, and the realization investment and the

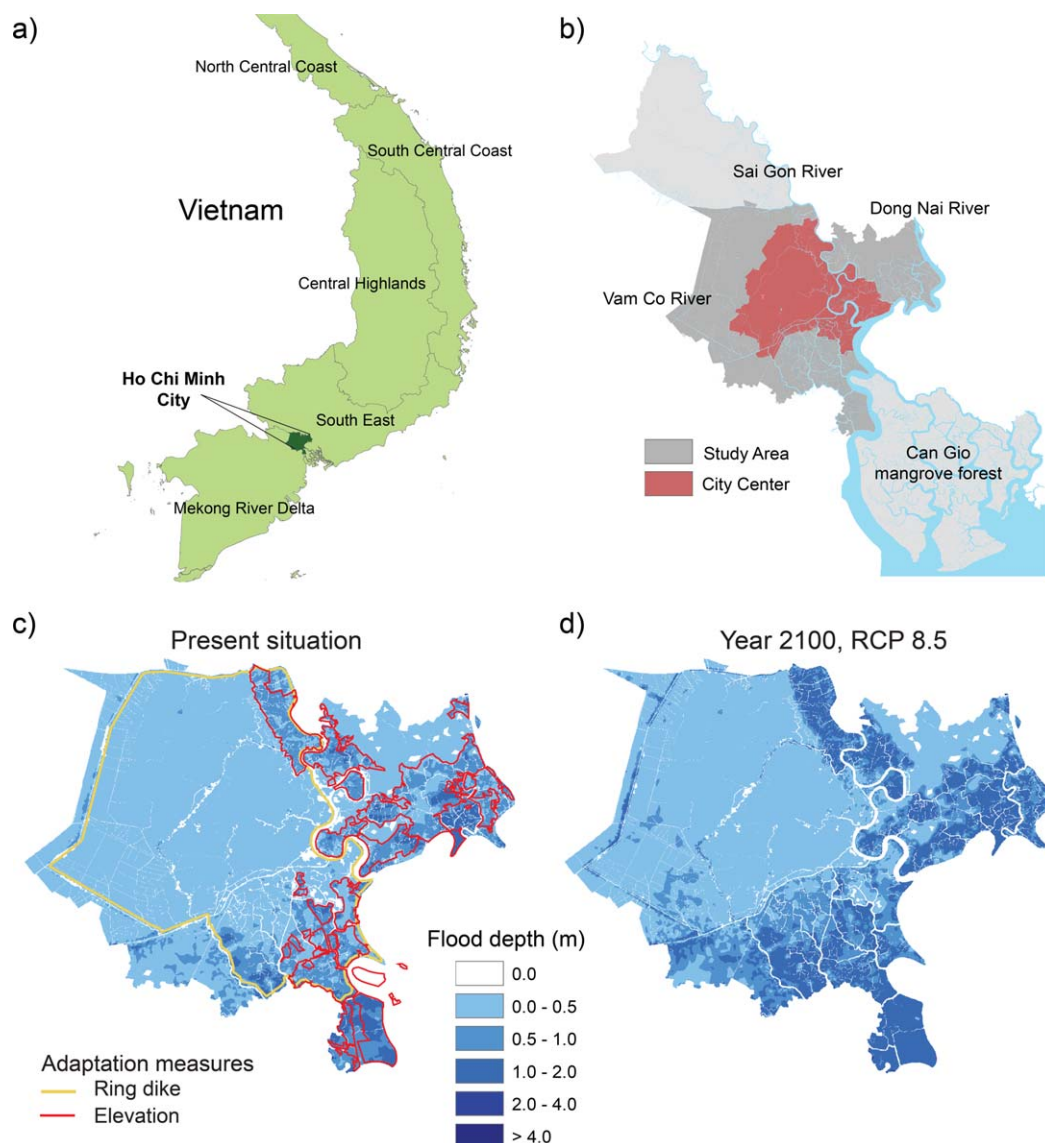


Figure 2. (a) Location of Ho Chi Minh City and (b) of the study area and the city center, and depth of the 100 year flood event: (c) in the present and (d) in the year 2100 for scenario RCP8.5. Also shown are and the locations of two of the adaptation measures simulated in this study: Ring dike (yellow line) and elevation (red lines).

maintenance represent the costs. We refrain from quantifying indirect economic effects and environmental and social impacts (see section 4).

For each measure, the net present value (NPV) is estimated, using

$$NPV = \sum_{t=1}^T \frac{(B_t - C_t)}{(1+r)^t} \quad (1)$$

where B_t is the benefit of a flood risk management measure in year t , C_t is its cost, r is the discount rate of future values, and the investment horizon is T years. The benefit in year t in this context is the avoided flood damage in year t , and the cost in year t includes the investment or construction costs in year t and yearly maintenance costs (for details of the costs see supporting information Table S4; Aerts et al., 2013; FIM, 2013d; Hillen, 2008; Hillen et al., 2010; Kreibich & Thieken, 2008; Mai et al., 2008). A positive NPV thus indicates that the sum of the discounted benefits exceeds the sum of the discounted costs over time, which implies that a measure generates positive net economic benefit.

A related indicator of economic efficiency of an adaptation measure is also calculated, the benefit/cost ratio (B/C). Because measures have different costs, prior to calculating the B/C, we apply the adjustment of Zerbe and Dively (1994) and normalize the benefits and costs of each measure as follows. For each scenario, we calculate a Δ_c for each measure, defined as the difference between its cost and the cost of the most expensive measure:

$$\Delta_c = \sum_{t=1}^T \frac{(C_{max\ t})}{(1+r)^t} - \sum_{t=1}^T \frac{(C_t)}{(1+r)^t} \quad (1)$$

where C_{max} is the cost of the most expensive measure. We then calculate B/C as the ratio between the sum of the benefits and Δ_c and the costs of the most expensive measure:

$$\frac{B}{C} = \left(\sum_{t=1}^T \frac{(B_t)}{(1+r)^t} + \Delta_c \right) / \sum_{t=1}^T \frac{(C_{max\ t})}{(1+r)^t} \quad (2)$$

This adjustment allows to use B/C to compare and accurately rank measures with very different investment costs.

If $NPV > 0$, then the $B/C > 1$. Both indicators are provided here since, while the B/C ratio shows the relative benefits per dollar invested in a measure, the NPV provides insight into the total net economic benefits that a measure generates in the long term. Because the discount rate for future costs and benefits used in NPV has been the center of intense debate in literature on the economics of climate change (van den Bergh & Botzen, 2014), we present our results under three discount rates: 5%, 2.5%, and no discount. The first is prescribed by the National Bank of Vietnam; the second is based on discount rates used in appraisals of flood risk management investments with a long time horizon (Lasage et al., 2014); and the third is included to understand the sensitivity of our results to variation in discount rates.

2.6. Adaptation Pathways

Using the results of the assessment of the adaptation measure, we adopt the approach of adaptation pathways (Haasnoot et al., 2013) to examine how the effectiveness of adaptation choices in HCMC may play out along the rest of this century.

Adaptation pathways are meant to support robust decision-making in the face of highly uncertain future developments, such as in adaptation to climate change. Pathways enable to explicitly consider the time-window (dependent on the rate of change in the system, e.g., SLR) in which each measure is expected to be effective, and to therefore analyze when it is possible and rational to switch from one measure to another, or to combine measures. For more details on the use of adaptation pathways, refer to Kwakkel et al. (2015).

3. Results

In this section, we report the main results for the various scenarios and time horizons, and for the various adaptation measures considered. Additional results for different values of parameters and assumptions are reported in supporting information Table S5.

3.1. Present and Future Floods

The flood modeling for four return-periods and five levels of SLR (0, 23, 49, 64, and 180 cm; Table 1) yields a total of 20 maps of the extent and depth of floods in HCMC. Figure 2 exemplifies the flood modeling results by comparing two 100 year flood maps, for the present and for year 2100 under scenario RCP8.5. As expected, the extent of the flood is larger and the flood level is deeper for longer return-periods, but these differences are even larger between scenarios (supporting information Table S5). For the 100 year flood in the present, 2.3% of HCMC is flooded by at least 1 m of water. By the end of the century, this increases to 11% for RCP8.5 and to 28% for RCP8.5 High-end. Higher water heads at the East Sea, during storm surges with longer return-periods and with higher sea levels in the future, entail deeper flood waters especially in the southern and eastern parts of the city, and along the main rivers. On the other hand, parts of HCMC that are presently considered critical, like the financial District 1 and the Tan Son Nhat international airport, do not see the largest increases in flood depths with SLR and with longer return-periods.

3.2. Socioeconomic Impacts Without Adaptation (i.e., Under Business-As-Usual)

The main impact results are expressed in terms of annual risk of economic damage and of potential casualties, integrated probabilistically from the values for the four return-periods analyzed, for the present and for the future scenarios and time horizons considered (Figure 3).

The magnitude of the economic damage increases greatly in all scenarios of the future, by a factor of 6–10 in year 2050 and by a factor of 15–60 in year 2100, depending on the SLR and socioeconomic scenario. In all time horizons and scenarios, socioeconomic changes appear to be more important than SLR in driving the increase in damage. However, the higher the SLR, the more prevalent the combined effect of these two drivers becomes.

Potential casualties increase by 3 to more than 5-fold in year 2050, and by 5 to more than 20-fold in 2100. Wider and deeper floods seem to be more important than higher flood velocities in determining these increases, as the latter change only marginally with SLR (see supporting information Figure S5). Because we assume stable (though denser) population for all future scenarios and time horizons, the proportion of the increase in potential casualties attributed to SLR and population growth is constant, 71% and 29%, respectively. Therefore, SLR prevails over socioeconomic changes in driving increase in potential casualties.

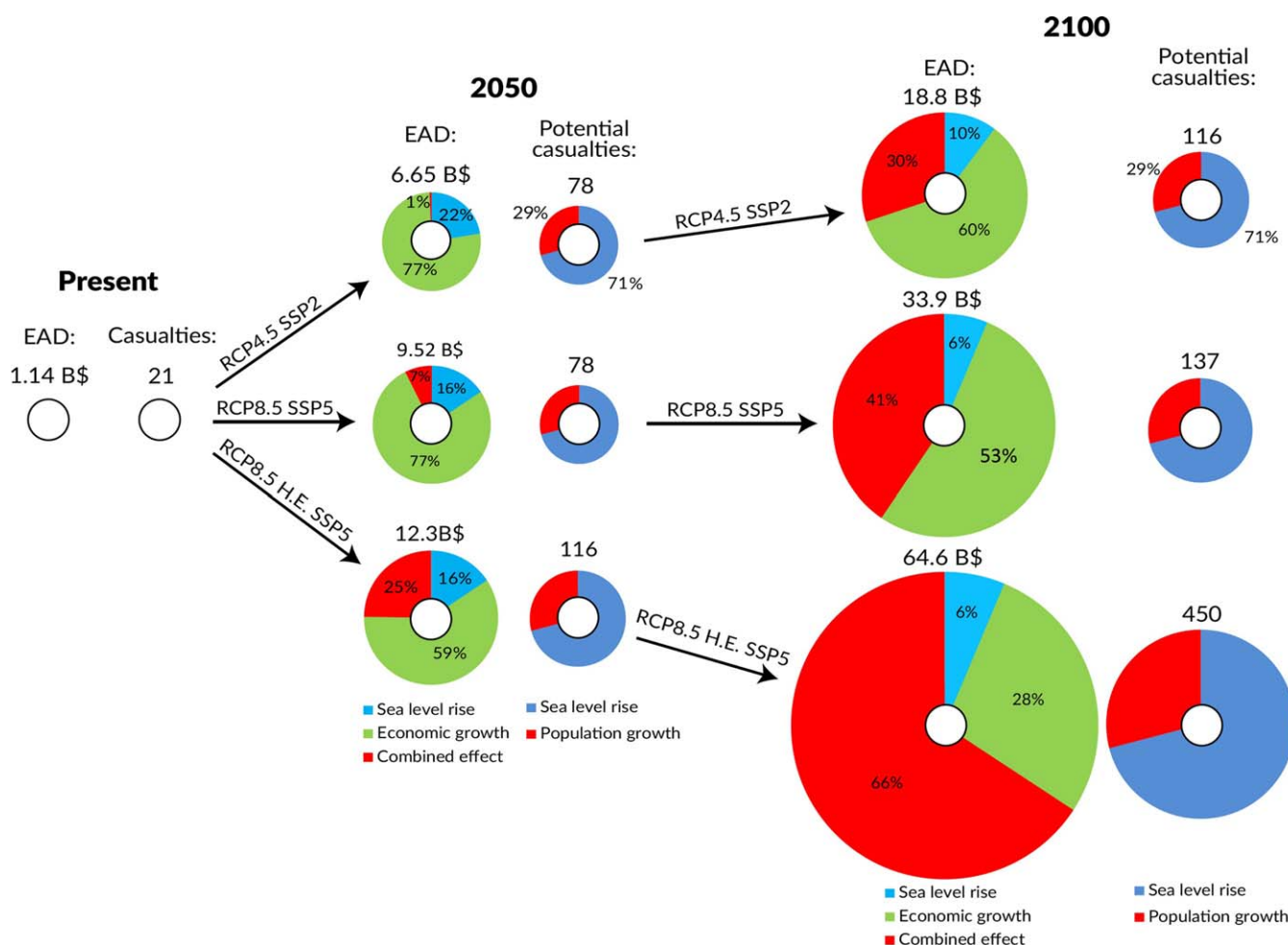


Figure 3. Evolution of impacts of sea level rise and of socioeconomic growth, in the business-as-usual situation, i.e., if no adaptation is undertaken. Impacts are expected annual damage (EAD, not discounted) and potential casualties, from the present until year 2050 and year 2100, for the three combinations of scenarios considered: RCP4.5 and SSP2; RCP8.5 and SSP5; and RCP8.5 High-end (H.E.) and SSP5 (see section 2.3). The size of discs is proportional to the amount of impact. The colors in the outer ring of the disc indicate the increase in impacts relative to the present (white discs), and they show the proportion of the increase attributable to each driver: sea level rise (blue), economic growth (green), their combined effect (red), and population growth (red). Across all scenarios, 29% of the increase in potential casualties is attributed to sea level rise, and 71% to population growth.

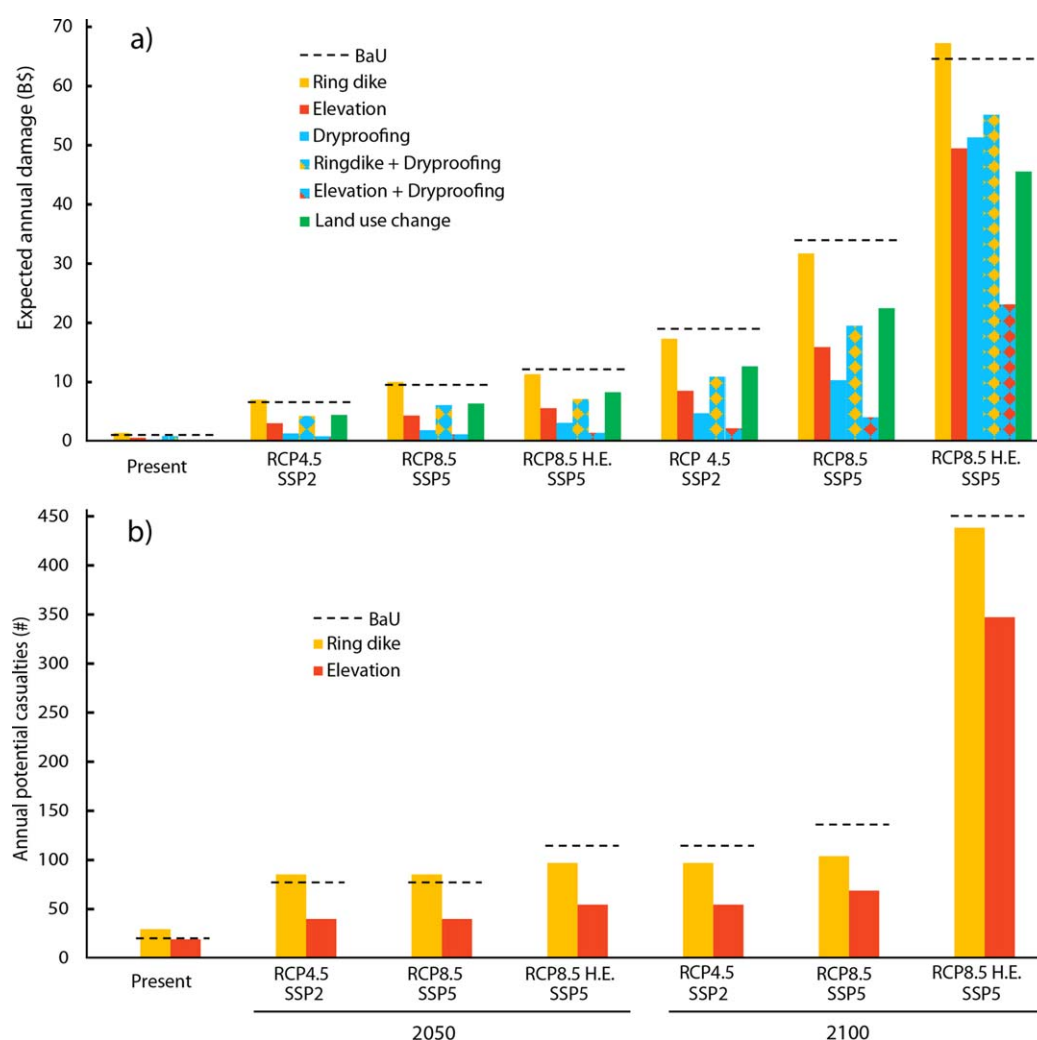


Figure 4. Performance of each simulated adaptation measure and strategy in reducing the future impacts of sea level rise as compared to the business-as-usual (BaU) situation, for the three combinations of scenarios: RCP4.5 and SSP2; RCP8.5 and SSP5; and RCP8.5 High-end (H.E.) and SSP5. We show the results for the indicators: (a) annual damage (not discounted) and (b) annual potential casualties.

In the worst-case scenario, i.e., RCP8.5 High-end and SSP5, both economic damage and potential casualties in our simulations increase massively, reaching about 65 B\$ and 450 potential casualties per year, due to much higher SLR than in the other scenarios.

3.3. Performance of Adaptation Measures

Figures 4a and 4b depict the reduction in expected annual damage and potential annual casualties, respectively, associated with each of the measures analyzed, as compared to the business-as-usual situation. The performance of each measure is described in the following subsections.

3.3.1. Ring Dike

If we consider the whole city, the ring dike is not an effective measure against annual damage and potential casualties across all scenarios and time horizons, as it only marginally reduces these impacts in scenarios RCP8.5 High-end in year 2050, and RCP4.5 and RCP8.5 in 2100. On the other hand, the ring dike is very effective within the dike-enclosed area (supporting information Figure S6), even in the case of very large floods of 1,000 year return-period. In this area, it reduces annual damage by 80–90% from the present until scenario RCP8.5 High-end in year 2050, or until scenario RCP4.5 in 2100. But it is less effective in scenario RCP8.5 in 2100, and useless in scenario RCP8.5 High-end in 2100. It prevents 40–60% of potential casualties in all scenarios except RCP8.5 High-end in year 2100, when it will not work. The reason for this differential effectiveness, within the dike-

enclosed area versus outside, is that while blocking flood waters from entering the central districts, the ring dike diverts waters to the surrounding areas, increasing flood depth especially east of the Saigon river.

3.3.2. Elevation

Elevating parts of HCMC (as shown in Figure 2c) is effective in reducing annual damages for the whole city by 52–55% in the present and in all future scenarios except RCP8.5 High-end, when it will only reduce it by 23%. Elevation also prevents a considerable portion of the population from being flooded by more than 1 m and reduces potential casualties by 35% in the present and by about 50% in all future scenarios except RCP8.5 High-end, when it saves 23%. Elevation is less effective than the ring dike in protecting the central areas of the city, because the areas elevated only partially coincide with the central areas (Figure 2).

3.3.3. Dryproofing Buildings

Dryproofing urban and rural houses and small businesses is highly effective in reducing annual damage, by 82% in the present and by 70–80% in all future scenarios save RCP8.5 High-end, when it only saves 20%. Since it is meant to protect the structure and content of buildings and people inside of them, dryproofing is uninfluential in reducing the extent and depth of flooding, and thus the potential casualties of people outside buildings.

3.3.4. Land Use Change

Implementing the master plan 2025 for land use generates a reduction in the annual damage of floods by 30–37% across all future scenarios and time horizons. As with dryproofing buildings, this measure does not influence the calculation of potential casualties.

3.3.5. Combination of Measures

By combining a ring dike + dryproofing buildings, a substantial reduction in annual damages is obtained, by 26% in the present and by 36–42% across all scenarios except RCP8.5 High-end at year 2100, when reduction is only 14%. Combining these two measures yields worse damage reduction performance than dryproofing alone, because the ring dike causes areas outside of it to flood at depths that overwhelm the dryproofing. However, these two measures combined do reduce potential casualties, as the ring dike alone does.

By combining elevation + dryproofing, the largest reduction in annual damage is obtained, by almost 90% in all future scenarios except RCP8.5 High-end at year 2100, when reduction will be 64%. Regarding potential casualties, elevation + dryproofing yields the same positive outcome as elevation alone.

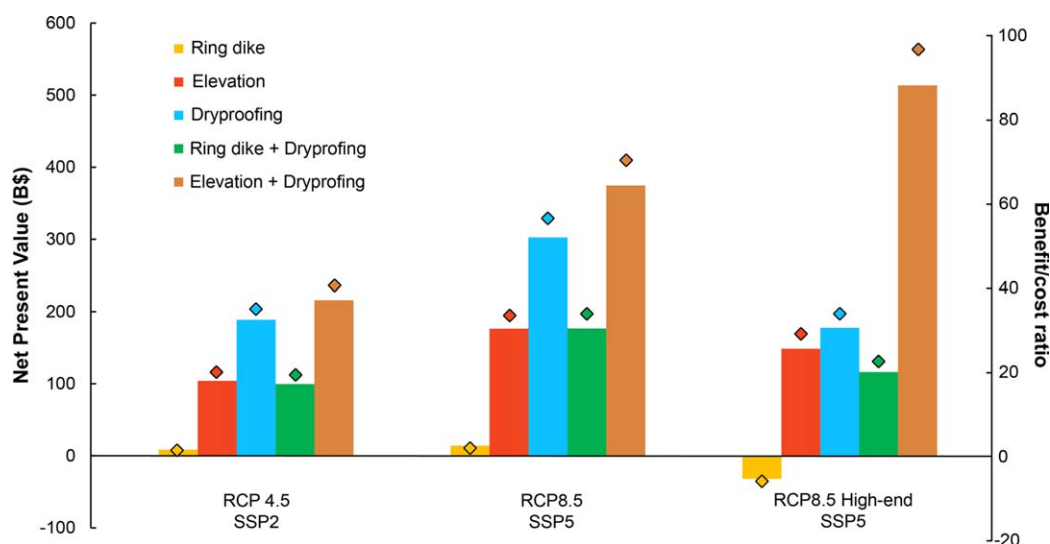


Figure 5. Summary of the economic appraisal of the adaptation measures investigated, for the three combinations scenarios RCP4.5 and SSP2; RCP8.5 and SSP5; and RCP8.5 High-end and SSP5, until year 2100, assuming the land use of 2010 (for the same results with land use of 2025 see supporting information Figure S7). We show the net present value (bars, left axis) and the adjusted Benefit/cost ratio (diamonds, right axis; see section 2.5) of each measure and combination of measures, for the discount rate of 2.5% (results with 0% and 5% discount rate are reported in supporting information Table S5).

We also calculated the combined effect of land use change (as per the 2025 map) with each of the other adaptation measures (supporting information Table S5). Land use change increases the effectiveness of the ring dike in all scenarios except RCP8.5 High-end in year 2100. It also increases the effectiveness of dryproofing across all scenarios. However, it reduces the effectiveness of elevation in all scenarios, mostly because changes in land use map occur in areas that would become elevated.

3.4. Cost-Benefit Analysis

The costs, benefit/costs ratio (B/C) and net present value (NPV) of adaptation measures until year 2100 are plotted in Figure 5 for the 2.5% discount rate. Note that the land use change measure is not included in the cost-benefit analysis because it is not possible to quantify its cost.

We calculate that the combination of elevation + dryproofing appears to be the most expensive, followed by elevation, ring dike + dryproofing, ring dike, and dryproofing, the cheapest.

All adaptation measures their combinations appear to yield benefits that substantially outweigh their costs, with the single exception of the ring dike in scenario RCP8.5 High-end. The economic performance varies widely between measures and between the three RCP/SSP scenarios considered. The ring dike shows the lowest B/C, ranging from negative 5 in RCP8.5 High-end to 4 in RCP8.5, and the lowest NPV, from 14 B\$in RCP8.5 to negative 32 B\$in RCP8.5 High-end. The combination of elevation + dryproofing shows the highest B/C, ranging from 41 in RCP4.5 to 97 in RCP8.5 High-end, and the highest NPV, from 514 B\$in RCP8.5 High-end to 216 B\$in RCP4.5. Large positive NPV indicates that adaptation could have positive long-term economic returns in the order of tens of B\$in the case of the ring dike, and of hundreds of B\$in the case of all other adaptation measures.

To understand how sensitive the economic appraisal is to land use, we also calculated the results using the planned land use map of year 2025 (supporting information Figure S7). While the NPV and the B/C are on average 50% lower when the 2025 land use map is applied, this varies depending on the adaptation measures and the scenario considered. The ring dike is the only measure that seems (slightly) more economically beneficial under the land use of 2025, except for the RCP8.5 High-end scenario. The cost-benefit analysis with discount rate of 0% and 5% yields values of economic performance that are about 2–3-fold

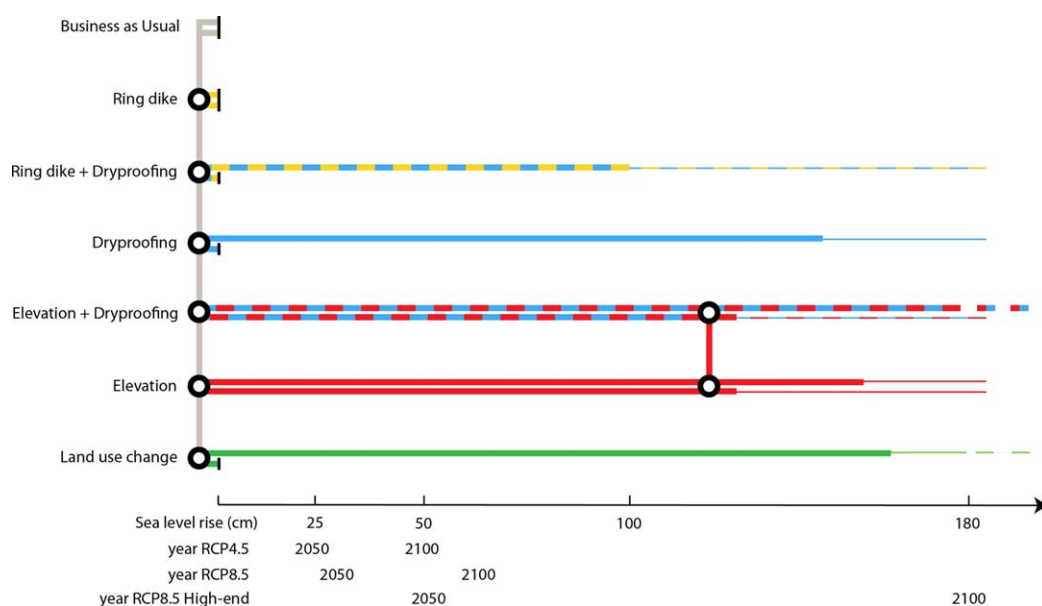


Figure 6. Proposed adaptation pathways for Ho Chi Minh City, plotted along horizontal axes indicating sea level rise, and scenario-dependent future time horizons. We consider the impact indicators: annual damage (top line of each measure); and potential annual casualties (bottom line of each measure). Dashed lines represent intervals where the effectiveness of measures is uncertain, because our simulations stop at 180 cm of sea level rise. Thinner lines represent intervals when effectiveness is much reduced. Circles represent points when it is plausibly possible to switch between measures and vertical black lines represent adaptation tipping points.

higher and lower than with 2.5%, respectively, although the rankings of measures across scenarios do not change.

3.5. Adaptation Pathways

The inputs to this portion of our analysis are the adaptation tipping points, which can be roughly estimated from our study of the effectiveness of the adaptation measures. These correspond to the point in the future when a given measure does not fulfill its function any longer. These points can be expressed on a temporal scale or along the progression of the climate variable under analysis (in our case, SLR). Also useful to the analysis are the economic insights we gain from the cost-benefit analysis of measures, and insights into their social and institutional feasibility.

Figure 6 depicts the adaptation pathways generated from our results, using annual damage and potential casualties as impact indicators. The ring dike, if implemented alone, is immediately ineffective (relative to other measures) at reducing both damages and potential casualties to the city as a whole. It must be kept in mind that the ring dike is nevertheless effective for buildings and people occupying the center of HCMC. It is possible to switch from the ring dike to the combination of ring dike + dryproofing, thereby effectively reducing damages until about 100 cm SLR, but not reducing the potential casualties, because dryproofing does not reduce the risk to people outside buildings. Dryproofing alone may achieve damage reduction up to higher SLR than ring dike + dryproofing because, as explained, the ring dike diverts more water to areas outside the center, causing dryproofing there to become less effective. Elevation alone may reduce both damages and potential casualties (well) beyond 1 m SLR, after which it is possible to switch to the combination of elevation + dryproofing, which should effectively reduce damages for longer. Change of land use in accordance with the 2025 plan, being effective at reducing damage, may be adopted parallel to other measures at any moment.

Investing in the ring dike leads to a lock-in situation, whereby the next step, besides increasing the height and strength of the ring dike, could only be to elevate areas at risk. However, shifting to the latter seems unreasonable because it would imply yet another large infrastructural investment. Also, if the ring dike is not expressly built with the possibility of future heightening, it is the only measure that is not flexible, i.e., it cannot be scaled depending on different SLR outcomes. On the contrary, elevation and land use can be realized progressively and are therefore more flexible.

Finally, it must be noted that the timely switch between adaptation measures critically depends on periodic monitoring of progressing SLR, its impacts, and of the effectiveness of measures in place (Haasnoot et al., 2013).

4. Discussion

While the impacts of flooding in HCMC are already severe, our study shows clearly that they will gradually worsen as climate-induced sea level rise proceeds. It appears from the analysis presented here that HCMC has two valid reasons to immediately undertake adaptation action. First, almost all measures considered in our analysis yield consistent reductions in the direct economic damage and potential casualties, under current and under future conditions. One notable exception is if scenario RCP8.5 High-end materializes, in which case none of the measures will reduce impacts satisfactorily (Figure 6). Second, most measures generate positive economic returns on investments, with benefits over the coming decades that outweigh the costs. Only the ring dike worsens the impacts in peripheral areas of HCMC until about 2050, yielding a negative return in the longer term, if it is implemented without being supplemented by other measures like dryproofing.

The choice of a discount rate has a large effect on the calculated B/C and NPV of the adaptation investments. The reason is that investments are made in the first years and are therefore only marginally discounted, while the benefits accrue stochastically each year up to year 2100 and are valued much lower (higher) when a higher (lower) discount rate is applied. However, applying a discount rate of 0, 2.5, or 5% does not change the ranking of adaptation measures based on their economic performance. In relation to this, it should be noted that the potential economic benefits of the adaptation measures, corresponding to avoided damages, may in reality be larger than we quantify here. Our estimation of the economic impacts is conservative in that it represents only the direct physical damage of floods. Ideally, costs of ex post flood

recovery should also be included, as well as indirect impacts of the flood event. The latter include job losses and the losses that propagate from the flooded economic activities to areas and sectors not directly hit by the flood. Including indirect impacts (Koks et al., 2015) and recovery costs (Nabangchang et al., 2015) can add up to notable amounts, but requires data not available to us, namely regionalized national accounting factors, to quantify indirect impacts. The development of a macroeconomic impact assessment for the region is left for future research.

On a similar note, the scope of our study excludes the assessment of impacts of SLR on the natural environment within or in the proximity of HCMC. The most valuable ecosystem in the area is the Can Gio mangrove forest (Figure 2). The viability of this forest will likely depend on the deposition of sufficient fluvial sediments to keep pace with SLR, and on the gradient between saline and fresh water. The impacts of a ring dike (FIM, 2013c) and other adaptation measures on these characteristics of the delta system should be analysed before deciding on implementation.

4.1. Policy Recommendations

The ring dike seems to align with the political objectives of the Ministry of Agriculture and Rural Development (MARD), which is currently promoting the MARD variant plan analyzed in our study, after having forgone a larger ring dike proposed under the earlier MARD plan. However, the city government and other stakeholders in the region, although pressed on the issue of flood mitigation, have recently manifested opposition to this plan. Main points of opposition are public resistance and limited experience in conducting large-scale infrastructural projects and in managing such a large polder area (i.e., land area below sea level). Also, the coincidence of multiple territorial administrations and of conflicting interests of stakeholders is seen as a problem. Further, floods and climate change adaptation in HCMC are managed across entities from the national to the district policy level, so that agreement on large investments takes time to materialize. The combination of the above factors has proven to hamper the decision-making in HCMC and has delayed implementation of flood protection (Ho et al., 2015). An additional barrier for the implementation of a ring dike, as identified in this study, is the potential increase of flood risk outside the diked city center, hence transferring flood risk to the external, mostly rural and poor areas, exacerbating local poverty and inequality. Research has shown that peripheral areas of the city are indeed more vulnerable to suffer acute consequences of floods (Tu & Nitivattananon, 2011), and generally lower income households seem to suffer higher flood risk (Kind et al., 2017).

For the elevation measure, equity should also be taken into account. Specifically, it should be prevented that areas with higher property value be differentiated and elevated, at the expense of less valuable areas that will become relatively lower and more exposed. Regarding the implementation of building-scale measures like dryproofing, it is not clear how long it would take to raise sufficient awareness among the concerned citizens, or for the local levels of government to bestow financial resources to improve the flood-preparedness of buildings. If these issues are not critical, dryproofing could be implemented relatively fast and at a low cost.

Any of the proposed adaptation measures, primarily elevation and dryproofing, will most likely constitute economically rational, rentable investments, bringing benefits, in terms of avoided damages, that markedly outweigh the implementation and maintenance costs incurred. This implies that the choice of a preferred course of action can take place substantially free of concerns regarding the long-term economic viability of the investment.

Important decision criteria might therefore include the following three items. (1) The amount of economic investment and the sufficient availability of funds for the cost-bearer, i.e., the government or the private household. In this regard, the ring dike is cheaper than the elevation of land, but dryproofing is the cheapest option and is relatively more effective. (2) The desired performance of the measure, i.e., how much impact reduction the city wants to achieve, for which indicators, and for which areas. Elevation protects more people than the ring dike, and is more robust, in that it reduces damages across more scenarios: the ring dike protects only the central areas; dryproofing prevents a lot of damage but does not address potential casualties, which we show to increase considerably in all scenarios, nor exclude flooding of streets and other public space. If the primary goal is to address the potential casualties, ad hoc measures should also be investigated, such as evacuation schemes (Lim et al., 2016). (3) The institutional feasibility involved. The ring dike and elevation measures fit well with the current institutional system, as the HCMC government can

decide on them free of consultation with neighboring provinces. Dryproofing, in contrast, can be realized by individual households, making implementation even simpler.

Institutional concerns that can be raised are that the ring dike, once completed, would stimulate migration toward the diked area (Di Baldassarre et al., 2015). This in turn would commit local institutions to increasing maintenance and pumping as SLR progresses. This, in combination with the fact that the ring dike will not eliminate flood risk completely even for the central districts, will spatially accumulate risk there in the long term. Regarding widespread dryproofing of buildings, it could be recommended that the government finance such an effort, as it seems the easiest and most egalitarian measure. On the other hand, it will not solve floods' disruption of city life nor the threat to safety, and should therefore be implemented along with structural measures. Elevation could offer opportunities for sharing the onus of adaptation between the government, which could realize it for communal spaces, and the private sector, which could be responsible for elevating private land.

In this context, the adaptation pathways analysis can illuminate decision-making, in the short and long term. A data-informed pathway, which complies with the institutional context of the city, would be the elevation of parts of the city at high risk, to be realized gradually as large urban areas are renovated, combined with widespread dryproofing of vulnerable buildings. The latter measure generates the largest positive net benefit across all scenarios. Parallel to this, a flood-wise land use plan should be developed, gradually enforcing the removal of exposed assets and people from risky low-lying areas. The option of building a ring dike may still be considered socially desirable, but the consequences for the outer parts of the city would need to be addressed by complementary measures.

5. Conclusions

We have modeled floods and their impacts in Ho Chi Minh City, for the present and with future scenarios of sea level rise and socioeconomic growth. The damages and potential casualties from floods are already large and have the potential to increase several folds in the coming decades. Different adaptation options show the potential to reduce impacts while performing very positively in terms of returns on economic investment. We therefore suggest that HCMC should take immediate action to mitigate present floods and to adapt to sea level rise. Our results show that none of the adaptation measures considered can effectively protect HCMC from flood impacts in the case of the High-end scenario of 180 cm SLR by 2100. In this scenario, alternative measures should be designed, implying higher costs of adaptation. By combining the evidence from our study with considerations about the institutional and socioeconomic background upon which decisions on adaptation are taken in this city, we formulate recommendations to inform adaptation planning in HCMC. Especially, the presentation of results in the form of adaptation pathways for the coming decades, and the inclusion of impacts on potential casualties offer policy-makers a vision of the long-term implications of adaptation decisions taken now or in the future.

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Erratum

The second author's name was misspelled in the originally-published version of this article. The error has been corrected, and this may be considered the official version of record.