Assessing Economic Benefit of Climate Adaptation for Urban Flooding in the Colombo Metropolitan Area, Sri Lanka

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Abstract *Flooding presents a growing challenge for rapidly urbanizing regions under intensifying climate change. This study assesses the economic benefits of climate adaptation through urban flood control in the Colombo Metropolitan Area, Sri Lanka. Using flood projections derived from five Shared Socioeconomic Pathway scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0 and SSP5-8.5), we integrate hydrodynamic modeling with high-resolution satellite imagery (10 m and 0.5 m) to map exposure and vulnerability of buildings across the Kalu Oya and Mudun Ela basins. Economic damage is estimated using structure–specific depth–damage functions for four building categories and compared under three protection levels: no measures, partial protection (1/25-year), and full protection (1/50-year). We found that full protection can reduce flood-related economic damage by approximately 40 – 71%, equivalent to avoiding losses of LKR 5 million to 5 billion , depending on the building type and scenario. The most significant benefits from full protection are gained wooden and unreinforced masonry (URM) houses. In contrast, commercial buildings and houses with concrete frames show smaller benefits (approximately 41–44%) for full protection level. Future climate scenarios affect risk, but structural vulnerability and protection level mainly determine how well we can adapt. These findings provide actionable evidence for urban planners and policymakers to prioritize cost-effective, risk-informed flood adaptation strategies in rapidly urbanizing coastal metropolitan areas.*

Keywords: shared socioeconomic pathways (SSPs), climate modeling, cost-benefit analysis, flood risk, disaster risk reduction, high-resolution satellite imagery, remote sensing.

Introduction

Urban areas in low- and middle-income countries are becoming increasingly vulnerable to flooding as climate hazards intensify and exposure to these hazards grows through rapid urbanization. Recent study estimates that approximately 1.24 billion people in South and East Asia face high flood risk associated with 1-in-100-year events, underscoring the scale of exposure and the development implications of catastrophic inundation (Rentschler et al., 2022). Sri Lanka faces these challenges, having experienced many severe floods over the past 20 years (Wijeratne & Li, 2022). One major flood in 2016 covered about 1,400 km², causing numerous fatalities and impacting hundreds of thousands of people, showing the serious social and economic effects (Alahacoon et al., 2018). The flood in 2017 disrupted communities and infrastructure (Platt et al., 2021). Within Sri Lanka, the Kelani River basin—which encompasses parts of the Colombo Metropolitan Area—has experienced around twenty major flood events in the past two decades (Wijeratne & Li, 2022). Urban areas in the Kelani River basin expanded by approximately 130% from 1995 to 2018 (Wijeratne & Li, 2022), which is similar to the rapid urban growth in South and Southeast Asia. Floods increase the risk to properties and worsen the negative impacts on quality of life, physical and mental health of the community

The average annual well-being losses due to fluvial flooding in Sri Lanka are estimated at US$119 million per year, exceeding the asset losses of US$78 million (Walsh, 2019), and asset losses are highly concentrated in the Colombo district. Flooding has a profoundly destructive impact on well-being, causing communities to fall into poverty temporarily and making it harder to eliminate poverty (Walsh, 2019). It is important to understand the economic effects of strategies to deal with flooding for better decision-making. Economic evaluation of adaptation pathways reveals how different strategies perform under various climate scenarios, guiding policymakers in selecting the most effective options (Babovic & Mijic, 2019).

Engineered flood control systems are known to protect against floods; however, measuring their benefits under future climate scenarios is challenging due to uncertainty (Linnenluecke & Griffiths, 2012). Urban resilience depends on how well a system absorbs, resists, recovers from heavy rainfall, number and distribution of drainage, and land cover (Boulange et al., 2025; Liang et al., 2024; Rimba et al., 2023; Rimba et al., 2021; Rimba & Yastika, 2020; Wu et al., 2022; Yao et al., 2023) . The primary planning question of constructing flood control system is not whether to invest, but rather which combinations of measures most effectively reduce losses per cost and for which groups or asset classes (Wu et al., 2022). For example, the benefit of the dam in the Bago River Basin of Myanmar; dam operations have reduced flood inundation areas by approximately 10% and decreased flood damage to buildings and agriculture by 40% and 10%, respectively (Shrestha & Kawasaki, 2020). Recent studies in Sri Lanka and the region have examined the links between urban sprawl and flood frequency, utilized hydrodynamic simulations to predict flood levels, and applied coupled circulation and wave models to estimate extreme water levels where long-term data are missing (Wijeratne & Li, 2022; Xu et al., 2014). Still, researchers require case studies that integrate climate scenario ensembles, hydraulic and hydrodynamic modeling, and high-resolution exposure mapping to assess the economic benefits of various protection levels for different building types.

Climate change exacerbates extreme weather patterns (Vavrus et al., 2024). It increases the risk of flooding and threat significant hazards to human life, infrastructure, and economic losses (Nozaki et al., 2023; Rimba et al., 2024; Rimba & Miura, 2017). Hence, climate change should be taken into account in flood control strategies. Effective flood control through climate mitigation not only reduces the immediate impacts of flooding but also contributes to long-term resilience against climate-induced disasters.

Shared Socioeconomic Pathways (SSPs) explore future climate uncertainties by examining various social and economic pathways and emission levels. They include various scenarios (such as SSP1 to SSP5) that demonstrate different levels of development and environmental issues, enabling us to analyze different scenarios (Marangoni et al., 2017; Rimba et al., 2024) . For instance, studies indicate that under different SSP scenarios, regions such as China may experience significant increases in annual mean temperatures and precipitation, highlighting the variability in climate impacts (Duan et al., 2021).

Some flood studies have been conducted in the study area. Wijeratne and Li (2022) employed a spatial regression model to investigate the relationship between urban growth and increased flood frequency in the Kelani River basin. Wagenaar et al., (2019) investigated the Kolonnawa basin that located in Colombo City (adjacent to the study area). They employed a joint hydrological and hydrodynamic model chain to simulate flood levels under various scenarios. The study included probabilistic inundation depth maps and assessed flood risks and damage associated with different adaptation measures and scenarios (Wagenaar et al., 2019). Another study in Colombo Metropolitan Area, they integrated ADCIRC (Advanced Circulation Model) and SWAN (Simulating WAves Nearshore) hydrodynamic models with Monte Carlo simulation to predict extreme water levels in Colombo, addressing the lack of long-term historical data for reliable flood modeling and estimates for 50, 100, and 200-year periods (Xu et al., 2014). However, no study has calculated the cost-effectiveness of future flood protection under an uncertain future climate. Thus, this study fills a gap in past research by being the first to analyze the cost-effectiveness of future flood protection using climate models. This approach helps decision-makers to evaluate the cost-benefit analysis of proposed adaptation measures in Colombo Metropolitan Area.

Study area

The study focuses on the Kalu Oya and Mudun Ela Basin, which are part of the Colombo Metropolitan Area. Colombo Metropolitan Area is the economic capital city of Sri Lanka, as shown in Figure 1. This urban region is densely populated and highly exposed to hydrometeorological hazards. The main flood exposure contributors are its low-lying terrain, poorly maintained drainage, and increasing impermeable surfaces. Gampaha District that includes the entire study area has experienced several major flood events in recent decades (Table 1). These floods have caused widespread damage to infrastructure and buildings. This study is a good example of how floods affect different building types and assesses the effectiveness of adaptation measures.

Flooding in the study area can occur due to heavy rainfall or high-water levels in the Kelani River. Flooding from heavy rainfall can worsen if the Kelani River levels are high or during high tides. High tides reduce the outflow capacity. Conversely, the situation can improve during low tide.

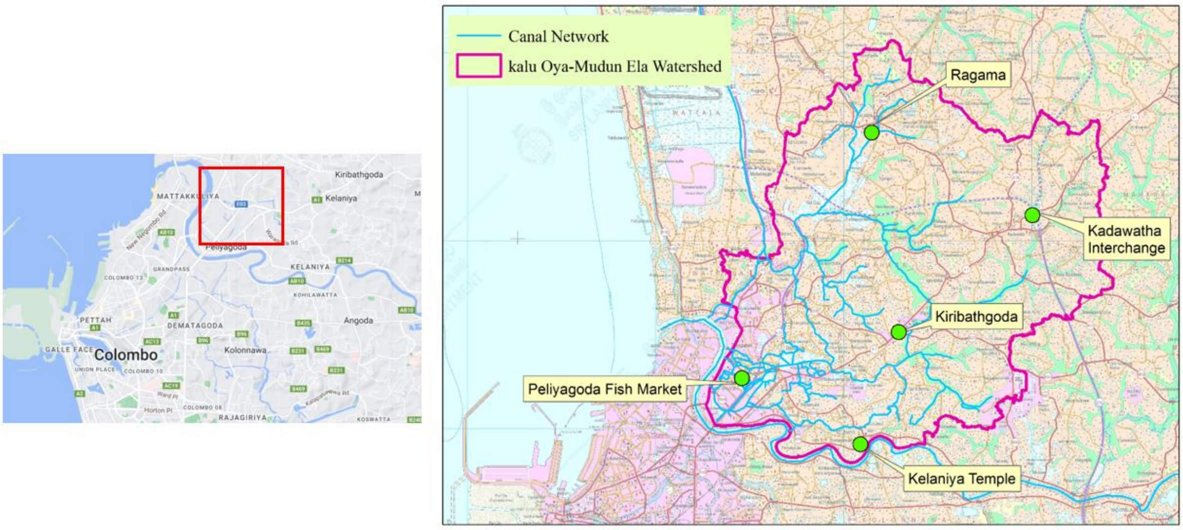

Figure 1: Study area. *Source: Authors*

Table 1: Major flood event by 2018 in Gampaha District

Rank	Date	Affected People
1	2010/5/16	99,927
2	2006/11/17	58,775
3	2016/5/15	57,101
4	2008/6/2	53,222

5	2013/5/4	48,289
6	2018/5/21	41,183
7	2016/5/16	35,860
8	2005/11/22	32,946
9	2017/5/26	32,133
10	2007/5/4	29,098

Methodology

This study utilized remote sensing data and GIS data, and climate modeling data.

a. Climate Modeling:

Precipitation data from atmosphere-ocean general circulation models (AOGCM) were acquired directly from the Coupled Model Intercomparison Project Phase 6 (CMIP6) to produce runoff. We selected five historical precipitation patterns and 11 Atmospheric and Oceanic General Circulation Models (AOGCMs) that provide the daily precipitation time series. The selected AOGCMS are CMCC-CM2-SR5, CMCC-ESM2, EC-Earth3, EC-Earth3-AerChem, EC-Earth3-CC, EC-Earth3-Veg, EC-Earth3-Veg-LR, INM-CM4-8, IPSL-CM6A-LR, NESM3, and TaiESM1. The AOGCMs provide 39 future climate scenarios, including five SSPs. Input precipitation patterns are extended in proportion to the daily precipitation of each return period. In this study, we used the precipitation amount within the 10km × 10km grid around Colombo. The future daily precipitation was estimated by multiplying the observed historical precipitation by the AOGCM precipitation change ratio between 1981-2010 and 2030-2070. Runoff was calculated in the MIKE rainfall-runoff calculation model. Future runoff estimates were subdivided into Shared Socioeconomic Pathway-Representative Concentration Pathway (SSP-RCP) scenarios, interweaving plausible climate and societal future scenarios. In this study,5 SSP-RCP scenarios were selected *SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0 and SSP5-8.5*to simulate the flood distribution and impact to Colombo Metropolitan Area. Additionally, we present the 75th percentile across all SSPs. The 75th percentile can help identify thresholds or targets that are more representative of higher performance or outcomes, rather than just the average. The inundation depth at the 75th percentile was chosen for each calculation grid. This resulted in a synthetic inundation map that integrates outputs from different scenarios.

b. Remote Sensing and GIS Data:

The remote sensing data and GIS data were collected from multiple sources. The building information was downloaded from the Global Human Settlement (GHSL) dataset. It was created in 2018 with a spatial resolution of 10 m (raster). Additionally, the building footprints were accessed from an open building. It was established in 2023, with a spatial resolution of 10 m (vector).

In QGIS, the building shape and height information were combined to create detailed building characteristics using the zonal statistics tool. The category of the buildings was determined based on the height data; for instance, if a polygon lacked height information, it was assumed that the building did not exist in 2018, and thus that polygon was excluded. Therefore, the building category reflects the data available as of 2018. The specific classes for building categories are presented in Table 2.

Table 2: Building type

No	GHSL ID	GHSL Classes	Building Category
1	11	Build spaces, residential, building height <= 3m	C-Wooden
2	12	Build spaces, residential, 3m < building heigh <=6 m	A-Unreinforced masonry walls (UMR)
3	13	Building space, residential, 6m < building heigh <= 15m	B-Concrete frame with unreinforced masonry fills walls
4	14	Building space, residential, 15m < building heigh <=30m	B-Concrete frame with unreinforced masonry fills walls
5	15	Building space, residential, building heigh > 30m	B-Concrete frame with unreinforced masonry fills walls
5	21	Build spaces, non-residential, building height <= 3m	C-Wooden
7	22	Build spaces, non-residential, 3m < building heigh <=6 m	D-Commercial building
8	23	Building space, non-residential, 6m < building heigh <= 15m	D-Commercial building
9	24	Building space, non-residential, 15m < building heigh <=30m	D-Commercial building
10	25	Building space, non-residential, building heigh > 30m	D-Commercial building

Source: Authors

d. Flood Modeling and Flood Damage Estimation:

Hydrological modeling was analyzed using MIKE Flood software, a tool for simulating river and urban flood scenarios, to predict flood extent under various time periods, climate change scenarios, and levels of flood protection (Table 3). The resulting flood map was then overlaid onto the building footprint layer to identify buildings exposed to flooding, using QGIS and Python-based geospatial libraries (such as GeoPandas). Economic damage estimation was calculated by applying structure-specific depth-damage functions, which relate floodwater depth to expected damage, to calculate losses under each scenario and protection level, as shown in Table 4.

Table 3: Policy measures/actions

Measurement		**Partial Measures**	**Full Measures**
Pump	[M3] Periyagoda (1m3/s)	○	○
	[K7] Kalu Oya (30m3/s)		○
[K3] Gate closed at Natha Canal		○	○
New gate	[K7] Down stream of Kalu Oya		○
River improvement	[K1] Kalu Oya-4 (case4)	○	○
	[K2] Natha Canal	○	○
	[M1] Mudun Ela	○	○
	[M5] Mudun Ela2	○	○
	[M2] Periyagoda Main (Dredging)	○	○
Retarding basin	[K8] 1		○
	[K8] 2		○
	[K8] 3		○
	[K8] 4		○
	[M6] 5	○	○
[K4] Flood diversion		○	○

Source: Authors

Table 4: Damage functions for structural damage

Building Category	Base Value (*LKR/m²*)	Damage Functions, (*D=Damage, x=Water depth*)
A – Unreinforced masonry walls (URM)	30,000	D = 10.55 ln(x)+11.487
B – Concreate frame with unreinforced masonry fill walls	80,000	D = 8.0826 ln(x)+9.0925
C – Wooden	6,000	D = 40.211 ln(x)+32.656
D – Commercial building	80,000	D = 4.875 ln(x)+7.7563
Temporary building	6,000	D = 10.55 ln(x)+11.487

Source: Center for Urban Water-Metro Colombo Urban Development Project

Results

This study utilized multiple datasets and scenarios from 11 general circulation models (GCMs), considering both partial (i.e., half) and complete (i.e., full) flood protection measures. Figure 2 presents the flood damage estimates for various SSPs and building types. It presents various levels of protection scenarios: no measure, half measure, and full measure. Building type B – Concrete frame with unreinforced masonry fill walls (URM) – was most affected, with the highest economic loss up to over 10 billion LKR (Sri Lankan Rupees). It was followed by D – commercial buildings, and A – buildings with unreinforced masonry walls (URM), respectively. Type C – Wooden buildings – showed the lowest losses compared to the others.

The benefit of flood protection can be seen in Figure 3. This benefit was calculated by differencing the flood outcomes under full-measure and no-measure scenarios to assess the impact of the full measure. Similarly, the benefit of the half-measure was determined by comparing the results of the no-measure and half-measure flood simulations. The pattern of benefit follows the same trend as in Figure 2, where type B – Concrete frame with unreinforced masonry fills walls – shows the highest benefit.

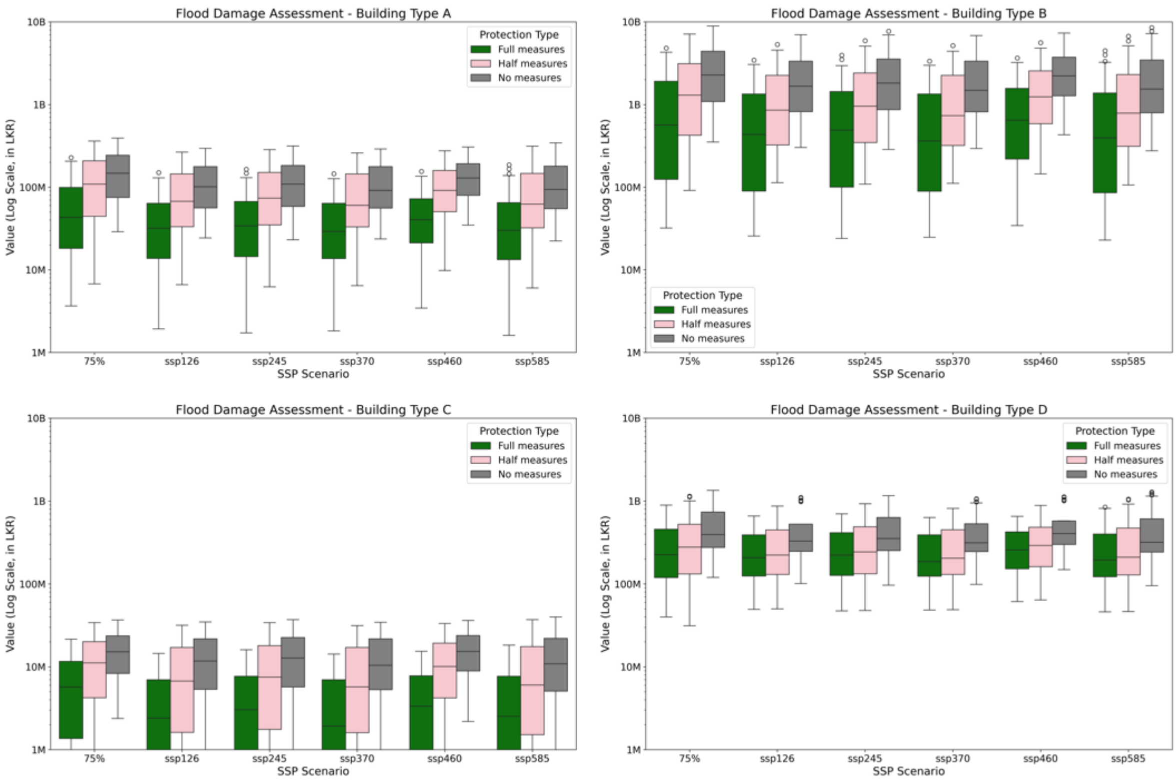

Figure 2: Flood damage assessment by building type and climate scenarios. The 75% value represents the 75th percentile across all SSPs. (*Source: Authors)*

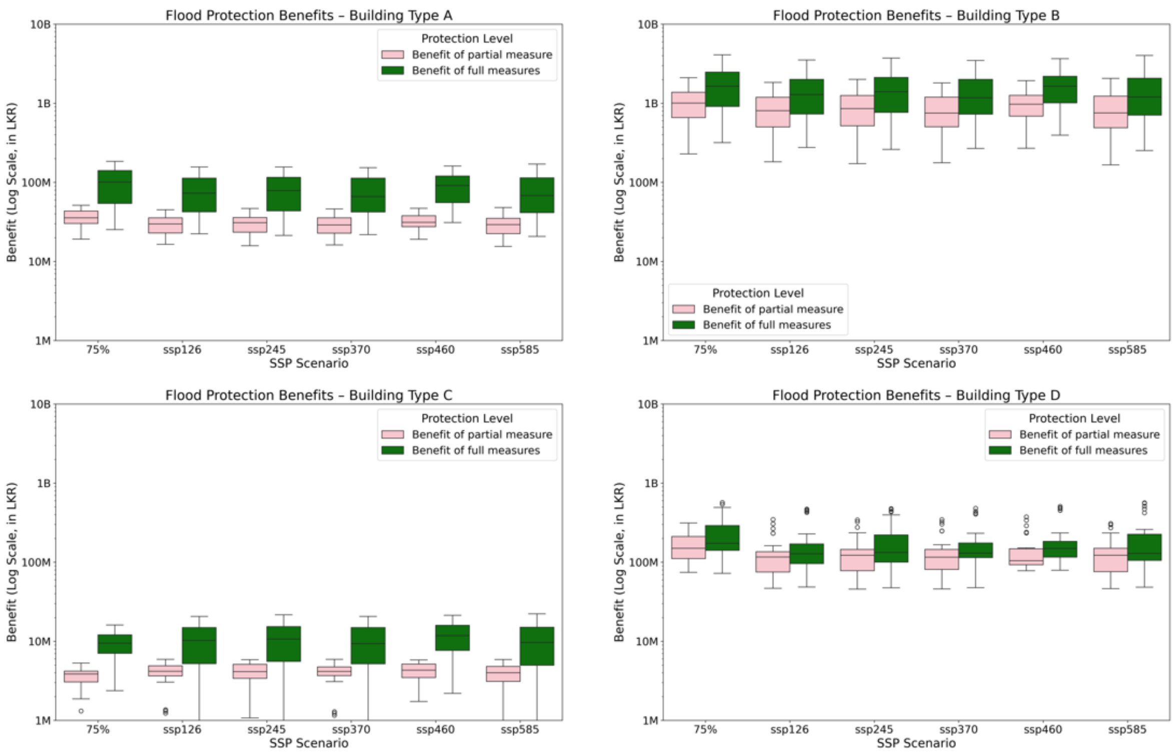

Figure 3: Flood protection benefit by building type and climate scenarios. The 75% value represents the 75th percentile across all SSPs. (*Source: Authors*)

The result shows that the simulation of full flood protection measures provides substantial economic benefits compared to either half measures or having no protection at all. These benefits are most significant for the most vulnerable building types, specifically C-Wooden and A-Unreinforced Masonry (URM) structures. For these types of buildings, damage can be reduced by up to 71% when full protection is used, compared to having no protection, as shown in Figure 4. For example, this could mean a reduction in potential damage from around LKR 1 billion to LKR 100 million for the most vulnerable types. When we compare protection levels, half measures provide some benefits over no protection. However, full measures are much more effective. The most significant improvement, a 40 – 71 % reduction depending on the scenario, occurs when we compare no protection to full protection. This significant reduction highlights the substantial cost savings and increased resilience. The benefits as shown in Figure 4 were calculated as percentage reductions for three comparisons i.e., (full vs no protection, half vs. no protection, and half vs. full protection). For each building type and SSP scenario, damages under full, half and no protection were averaged across 11 GCMs and five rainfall pattens.

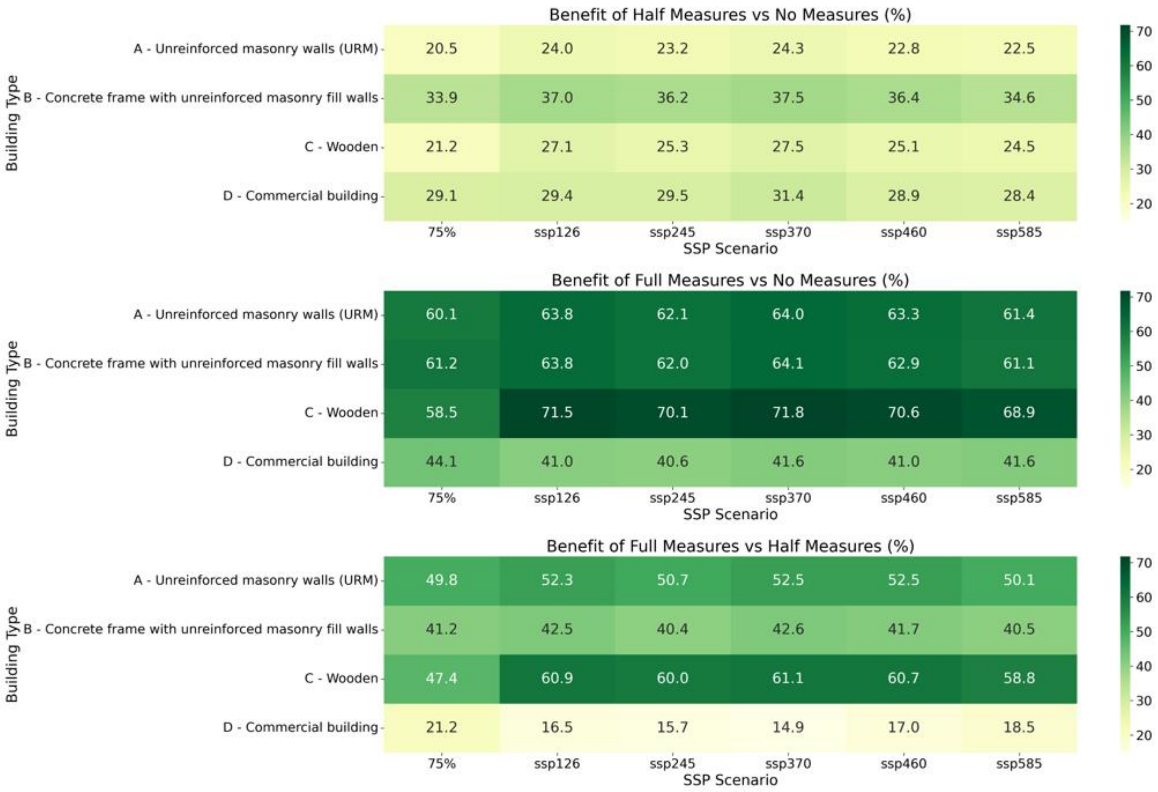

Figure 4: Flood benefit percentage by building type and climate scenarios. The 75% value represents the 75th percentile across all SSPs. *Source: Authors*

In contrast, the results show that commercial buildings tend to benefit less in relative terms from full measures. Their inherently more robust construction means that flood damage is lower, even without full measures. For example, expected losses for commercial structures range from LKR 80 millions to 800 millions without measures and are reduced by about 28 - 31% with half measures.

Another finding is that the SSPs, which reflect different feasible futures for climate and socioeconomic development, do not strongly influence the overall pattern of benefits. Although total damage may vary slightly across scenarios, the desirable actions are clear. The national government should aim for providing the full measures and, in collaboration with local governments, incentivize the construction of buildings with strong structures and the reinforcement of weak structures. Full protection is more effective than partial protection, and the type of buildings is always a crucial factor. It is recommended to focus on these drivers as they are more important determinants of flood risk outcomes.

Discussion

a. Benefit of building type analysis

This study calculates the benefits of flood adaptation across two basins in the Colombo Metropolitan Area using high-resolution exposure data and structure-specific depth–damage functions under multiple SSP scenarios and protection measures. Three robust insights emerge from this study. First, full protection (1/50) yields large reductions in direct structural losses—typically on the order of 40–71% relative to no measures—especially for the most vulnerable building (C-Wooden and A-URM). Second, partial measures (1/25-year) deliver the similar level of benefits for concrete buildings (B- Concrete frame with unreinforced masonry fill walls) and commercial buildings (D-Commercial) compared with the full measure. Third, although SSPs affect overall risk levels, the order of benefits remains stable, with structural vulnerability and protection level being the most important factors, while the scenario choice has a lesser impact. These results highlight an important policy message: in cities with limited data, focusing on building types and matching protection to vulnerability can lead to significant benefits.

The extra benefits for C-Wooden and A-URM structures come from two factors. First, these buildings are fragile, so even small reductions in flood depth can prevent much damage. Second, these buildings are mostly located in lowland areas with high flood vulnerability. Therefore, when flood protection measures are installed in these high-risk areas, these buildings will benefit the most. In contrast, B- Concrete frame with unreinforced masonry fill walls and D-commercial buildings are usually taller and more flood-resistant, and small depth reductions do not make as much of a difference. These factors explain the consistent pattern across scenarios and support the need for tailored protection strategies.

b. Relationship to prior work

The study shows that the benefits of adaptation depend more on building vulnerability and protection measures than on SSP scenarios. This aligns with other evidence that local factors, such as exposure, vulnerability, and the location of assets, typically have a greater impact on short- to medium-term flood losses (Bernardini et al., 2024; Rimba et al., 2023). The significant benefits for vulnerable areas match experiences in other Asian cities, where small drainage improvements and flood gates greatly reduced losses in vulnerable neighborhoods (Boulange et al., 2025; Rimba et al., 2023). Our study provides additional detail by showing how the value of upgrading from partial to full protection varies depending on the type of building, enabling more effective and affordable planning of upgrades.

c. Policy implications: advancing flood risk reduction

The results of this study provide clear and actionable guidance for policymakers seeking to reduce urban flood risk in the Colombo Metropolitan Area and other rapidly urbanizing regions. In the study area, house types and the level of investments in flood protection infrastructure had greater impacts on resulting flood damages than the difference in future climate and socio-economic scenarios did. The results may be different in other river basins, however. Nonetheless, this study illustrated the usefulness of the scenarios-based analysis in identifying effective flood risk mitigation measures.

Flood protection needs to be part of wider urban planning. Stronger building codes, limits on construction in flood-prone areas, and incentives for safer building designs can complement flood protection infrastructure and reduce future risks. While flood protection infrastructure requires more investment at the start, it saves much larger costs in the long run by avoiding repeated flood damage. It should be treated as an economic development measure, not just a disaster response, because it protects livelihoods and reduces future recovery costs.

Limitations

This study identifies several limitations that frame the interpretation and suggest future refinements. The building exposure dataset reflects conditions around 2018. Future exposure growth and asset value escalation are not explicitly modeled; as such, future losses may be under-estimated where development continues in flood-prone zones. In this study, the relationships of depth–damage functions that used are drawn from local project sources and applied uniformly within each category. Actual damage can vary with construction quality, maintenance, and specific design features (e.g., elevated ground floors). We retain the current study and do not extend it. Moreover, the pump and gate operations are represented at the level of protection settings. Real-time operational decision-making and failure risks (e.g., power outages) are not explicitly simulated.

Conclusion and Recommendation

This study demonstrates that full flood protection measures (1/50-year) are more effective than partial measures (1/25-year) or having no protection. Across all climate scenarios and building types, full protection consistently delivers the greatest reduction in losses, with particularly strong benefits for vulnerable wooden and unreinforced masonry (URM) houses, where potential damages can be reduced by 58–71%. Even for stronger concrete-frame and commercial structures, full protection still prevents substantial economic losses compared to partial protection.

These results show similar findings across all SSPs scenarios, meaning that flood protection infrastructure is a robust measure even under uncertain climate and socioeconomic futures. The dominant drivers of resilience factor in the study area are structural vulnerability and the level of protection provided. Hence, we concluded that prioritizing full measures is both a robust and effective strategy. Investments in partial measures may offer significant benefits as the first step toward the future upgrade to the full measures.

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