



Research article

The cost of flooding on housing under climate change in the Philippines: Examining projected damage at the local scale

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ABSTRACT

While the Philippines has made significant strides in proactive disaster risk reduction measures, current planning actions are undertaken primarily based on historical flood risk. There are gaps in understanding how the escalating impacts of climate change will alter flood dynamics. This study examines shifting local flood risk patterns in the Municipality of Carigara in Leyte. We quantify probabilistic flood damage on residential structures for early, mid-, and late-term flood scenarios under RCP4.5 and RCP8.5 pathways. By utilising localised housing vulnerability functions, we assess risk trends at a household level, considering concrete, light material, and elevated light material housing typologies. Our results indicate a 3 % decrease in future flood damages to residential structures under RCP 4.5 and a 34 % decrease in damages under RCP 8.5 by 2100 attributable to climate change for 100-year flood events. These shifts highlight the nuances of regional changes in flood damages over the next century. The findings provide insights into how localised climate-risk assessments for municipalities might be established as entry points to inform climate change policies and projects. Through established mechanisms such as Local Disaster Risk Reduction Management Funds (LDRRMF) in the Philippines, we propose methods of climate-informed decision-making for local government units to minimise damage for future climate scenarios.

1. Introduction

Climate change and extreme weather events cost the global economy an estimated USD 143 billion annually, a figure projected to exceed USD 400 billion by 2030 (Mahmoodi et al., 2023; Newman and Noy, 2023; Nguyen et al., 2024; UUSC, 2023). However, these anticipated damages are not inevitable. Proactive and appropriate investments in disaster risk measures have the potential to mitigate these losses significantly (UNISDR, 2015). It is increasingly crucial to quantify disaster risk attributed to climate change and how expected changes manifest at a local level to ensure informed decisions are made in current planning efforts (Aggarwal and Prasad, 2023; Yan et al., 2023; Noy et al., 2024; Thomas, 2024).

The impact of flood hazards accounted for 44 % of all global disasters and resulted in USD 651 billion in recorded economic losses between 2000 and 2019 (CREG and UNDRR, 2020). Asia is among the highest-risk regions, with numerous studies highlighting the continuous

impacts of both pluvial and fluvial flooding on populations (Ashraf et al., 2017; Budiyo et al., 2015; Cao et al., 2022). Studies in Vietnam (McElwee et al., 2017; Nguyen et al., 2024), India (Guhathakurta et al., 2011; Pal et al., 2022), Japan (Mori et al., 2021; Tezuka et al., 2014) and Indonesia (Kefi et al., 2020; Wijayanti et al., 2017) underscore the significant economic and social consequences of flood impacts, which are anticipated to be exacerbated by the effects of climate change (Muis et al., 2015; Arnell and Gosling, 2016; Hu et al., 2018; Pariartha et al., 2023; Nguyen et al., 2024). Projecting the impact of future flood events under climate change is essential for the development of optimal decision-making processes, thereby aiding potential adverse consequences (Mehryar and Surminski, 2022; Zia et al., 2023; Janizadeh et al., 2024).

During flood events and other natural hazards, housing is vital in stabilising communities and key to supporting livelihoods (Ahmed, 2011). Homes enable communities to cope with and recover from these calamities (Elmer et al., 2012; Pryce and Chen, 2011; van den

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Nouwelant and Cibir, 2022). However, constructing resilient and durable residential structures poses a challenge, particularly for those with limited access to adequate resources and safer land (Chmutina and Rose, 2018; Mitchell et al., 2015; Porio, 2011; Schilderman and Lyons, 2011; Shrestha et al., 2021). This challenge often results in adopting various building and construction typologies (Proverbs and Lamond, 2017). Damage analysis specific to non-engineered structures – those constructed without formal oversight or enforceable building regulations – is often less documented in both policy and literature as a result of data scarcity (Hadlos et al., 2023). When incorporating these types of structures into risk assessments, the use of generalisable datasets from urbanised areas may over- or under-estimate probable risk from disasters as they may fail to capture variances in building attributes. There is a growing need to capture informal housing and more localised housing typologies in quantifying climate change damage (Besarra et al., 2024).

The Philippines is widely recognised as one of the most hazard-prone countries globally, and it is acutely susceptible to adverse climate change impacts. National projections indicate a considerable increase in flood severity over the next century in some regions (Eccles et al., 2019; Tolentino et al., 2016; World Bank Group and Asian Development Bank, 2021; Yumul et al., 2013). Eckstein et al. (2021) placed the Philippines among the top four countries to be impacted by the long-term effects of climate change. These impacts are expected to primarily stem from an increase in the intensity and duration of storms, floods and extreme weather, leading to substantial economic impacts, which have already been estimated at over USD 3.1 billion in losses in the Philippines per year over the last two decades (Eckstein et al., 2021; Tabari, 2020).

The Philippines government has dedicated significant resources to minimising the impacts of disasters through policy development, institutional mechanisms, and investing in disaster preparedness (Alcayna et al., 2016; Opdyke et al., 2022). The country has made significant strides in streamlining climate change adaptation and disaster risk management through the Climate Change Act of 2009 (Republic Act No. 9729) and the Disaster Risk Reduction Management Act of 2010 (Republic Act No.10121) which facilitate and guide responses through government at the national, provincial, and local levels (NDRRMC, 2011; Raquedan, 2010; Doberstein et al., 2020). The policies align with global institutions such as the Sendai Framework. These efforts have been complemented by the dissemination of projected provincial-level climate change impacts by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (DOST-PAGASA et al., 2022).

However, despite these legislative frameworks, there are still gaps in integrating climate change-based scenarios into disaster risk management. There remains a limited understanding and guidance of how natural hazard patterns will change under climate change and what community actions should be to respond to these changes (Lagmay et al., 2015; Ranger et al., 2011). Currently, geohazard maps provided by the Philippines Mines and Geosciences Bureau (MGB) – the agency responsible for producing hazard maps used to inform local land use plans – are based on single-scenario susceptibility maps, which do not fully encompass the range and projection of climate-related risks faced by municipalities. Consequently, implementing data-driven climate change risk assessments at the municipal and barangay (community) levels has been slow due to the re-interpretation of historical climate projections. This re-interpretation, carried out by local scientists and policymakers, impacts and shapes local meaning by influencing how residents perceive climate risk. (Combest-Friedman et al., 2012; Dujardin et al., 2018; Grefalda et al., 2020).

Estimating future changes in local flood risk under climate change damage is complex and multifaceted (Stott et al., 2016; Janizadeh et al., 2021; Lahsen and Ribot, 2022). While controlling exposure is important to reduce flood risk (Cienfuegos, 2023), capturing the vulnerability of assets can play an equal role in developing solutions. With advancements in global flood projections offering comprehensive insights into how flood damages might change in the future (Eccles et al., 2019; Gaur

et al., 2018; Hirabayashi et al., 2013; Zhou et al., 2019), there is also a need to consider how these changes interact with community vulnerabilities to fully capture changes in flood risk. Evidence of hydrological changes is already manifesting. In the Philippines, Hong et al. (2022) projected that 1-in-20 and 1-in-17 year heavy rainfall events will become 1-in-16 and 1-in-14, respectively, by 2100. Despite an expected increase in flood frequencies in the Philippines, regional climate impacts are expected to vary (DOST-PAGASA et al., 2022). For instance, it is anticipated that rainfall experienced in some regions in Luzon will increase in the near future but decline as much as 900 mm annually in the latter half of this century. In comparison, the Visayas and Mindanao regions are expected to experience drier conditions over the next century (ibid). As evidence of these changes, Yumul et al. (2013) observed abnormalities in weather patterns in the Philippines in 2009, with the Luzon region experiencing increased precipitation and Mindanao facing drought conditions. These observations are reinforced by Tolentino et al. (2016) who emphasise the dynamic nature of climate-induced changes in flood exposure. Shifting flood hazard profiles are also driven by changes not only in total annual precipitation but also in frequency, duration, and intensity of rainfall events (Hirabayashi et al., 2008).

Approximately 60 % of the Philippines' land area and 74 % of the population are exposed to one or more natural hazards (GFDRR, 2011). The linkages between housing and climate change play an important role in understanding future risk. To respond to the need for localised assessments of flood damage of housing under climate change, this research narrows on a municipal-level case study to ask: *What are the projected impacts of climate change on housing flood risk?* To answer this question, this research aimed to examine the spatial and temporal changes in flood risk for housing stocks due to climate change in the Municipality of Carigara, located in the Province of Leyte. This research offers an approach to quantifying damage attributable to climate change, specifically for pluvial and fluvial flooding. We first adopt downscaled dynamic climate models to develop short-, medium-, and long-term projections of flood hazards for Representative Concentration Pathways (RCPs) 4.5 and 8.5. Combining these with previously developed residential building vulnerability functions for Leyte, we analyse risk to residential structures and compare anticipated shifts in the expected probability of damage and cost from floods. Our results offer the first localised case in the Philippines to quantify the costs of damages from climate change to residential building stocks. Through a comprehensive analysis, we shed light on the evolving risk landscape for residential structures and quantify these damages for non-capital regions, which are generally overlooked.

2. Methods

This research employed a spatial risk assessment to examine probabilistic residential flood damages under climate change scenarios in the Municipality of Carigara. We first derive our baseline for *flood hazards* through 5-, 25-, 50, and 100-year rainfall return periods, focusing on flooding extent and inundation depth. Utilising RCPs 4.5 and 8.5, we simulate flood extents and depths for each pathway under early (2020–2039), mid (2046–2065), and late (2080–2099) timescales, which are validated through household surveys. Second, we employ the use of OpenStreetMap (OSM) and building classifications from the local government unit (LGU) to obtain building footprints, narrowing our *exposure* unit of analysis to residential structures. Last, we reclassify building stocks obtained from OSM and the LGU to align with localised building typologies identified in Besarra et al. (2024). This enabled *vulnerability* functions to be assigned to each residential structure. Cost estimations for the defined residential structures were derived from interviews with local suppliers and workshops with the LGU. Using these components together, we spatially analysed risk for the four-baseline and 24-climate projected scenarios to derive corresponding expected total municipal residential losses. Below, we first provide an overview of the study (seen in Fig. 1), describe our hazard, exposure, and

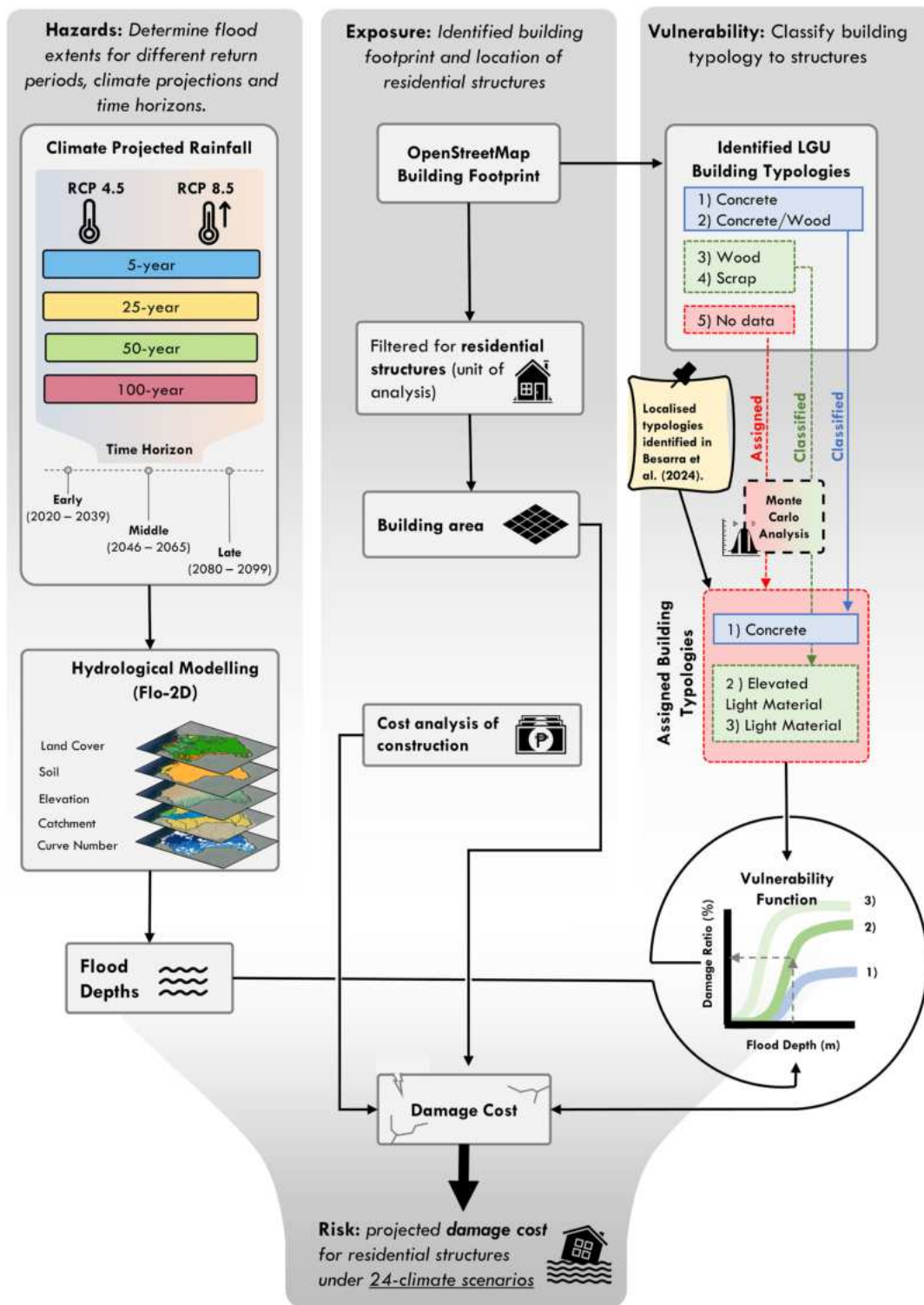


Fig. 1. Methodology overview.

vulnerability data, and then outline our analysis used to unpack shifts in flood risk.

2.1. Study area

While flood hazards are not unfamiliar to Filipino communities, the Eastern Visayas Region (Region VIII) remains highly vulnerable to flood impacts, having one of the highest poverty rates and prevalence of housing vulnerability in the nationally (Healey et al., 2022, 2023). The

Province of Leyte is a mountainous region with low-lying coastlines. This topography renders municipalities in coastal areas extremely susceptible to flooding. High central elevations contribute to rapid run-off during seasons of heavy rainfall, which can lead to pluvial flooding in low-lying areas. Additionally, river systems throughout the province can result in overflow causing fluvial flooding (Bentoso et al., 2021). Carigara is situated in northern Leyte and is composed of 49 barangays – the smallest administrative divisions in the Philippines. The municipality had a population of 54,656 and over 11,000 residential structures as of

2022, and serves as a central trading hub for surrounding municipalities (PSA, 2021). The coastal town lies at the centre of shallow Carigara Bay, intersected by the Lindong River and surrounding streams, which pose a source of pluvial flooding.

2.2. Data collection

Disaster risk can be conceptualised through constituent components of hazard, exposure, and vulnerability (Birkmann, 2013). Our data encompassed (1) *hazard inputs*: drawing upon elevation, drainage networks, landcover, soil types, historical rainfall, and regional climate models (RCMs), (2) *exposure units*: residential building footprints and (3) *vulnerability functions*: reflections of local flood depth and damage relationships based on housing typology. We describe each of these below.

2.2.1. Flood hazards

This section describes the data used to model pluvial and fluvial flooding. The section highlights the estimation of cost values for different housing typologies.

2.2.1.1. Elevation data. Digital elevation model (DEM) data for flood models drew upon three sources: (1) 2-m resolution (downsampled from 1-m) photogrammetry collected by the research team in July of 2022 (Opdyke and Besarra, 2024), (2) 2-m resolution (downsampled from 1-m) light detection and ranging data (LiDAR) from the University of the Philippines Disaster Risk and Exposure Assessment for Mitigation (DREAM) Project (DOST-UP, 2016) and (3) 6-m resolution (downsampled from 5-m) interferometric synthetic-aperture radar (IfSAR) from the National Mapping and Resource Information Authority (NAMRIA, 2013). IfSAR data can be requested from NAMRIA. The coverage of these DEMs is shown in Fig. 2. The photogrammetry data covered 4.6 km² of coastal and urban barangays, LiDAR data covered 11.6 km² of floodplain regions, and the IfSAR data covered the remaining 178 km² upland areas. Digital urban drainage canal networks were available from previous mapping efforts of the research team and local government in 2019, details of which can be found in See et al. (2020). The data includes the dimensions and conditions for drainage networks, which are available on OpenStreetMap. These networks were confirmed to be up to date with the local government and have been routinely updated. Drainage channels were then burned into the DEMs.

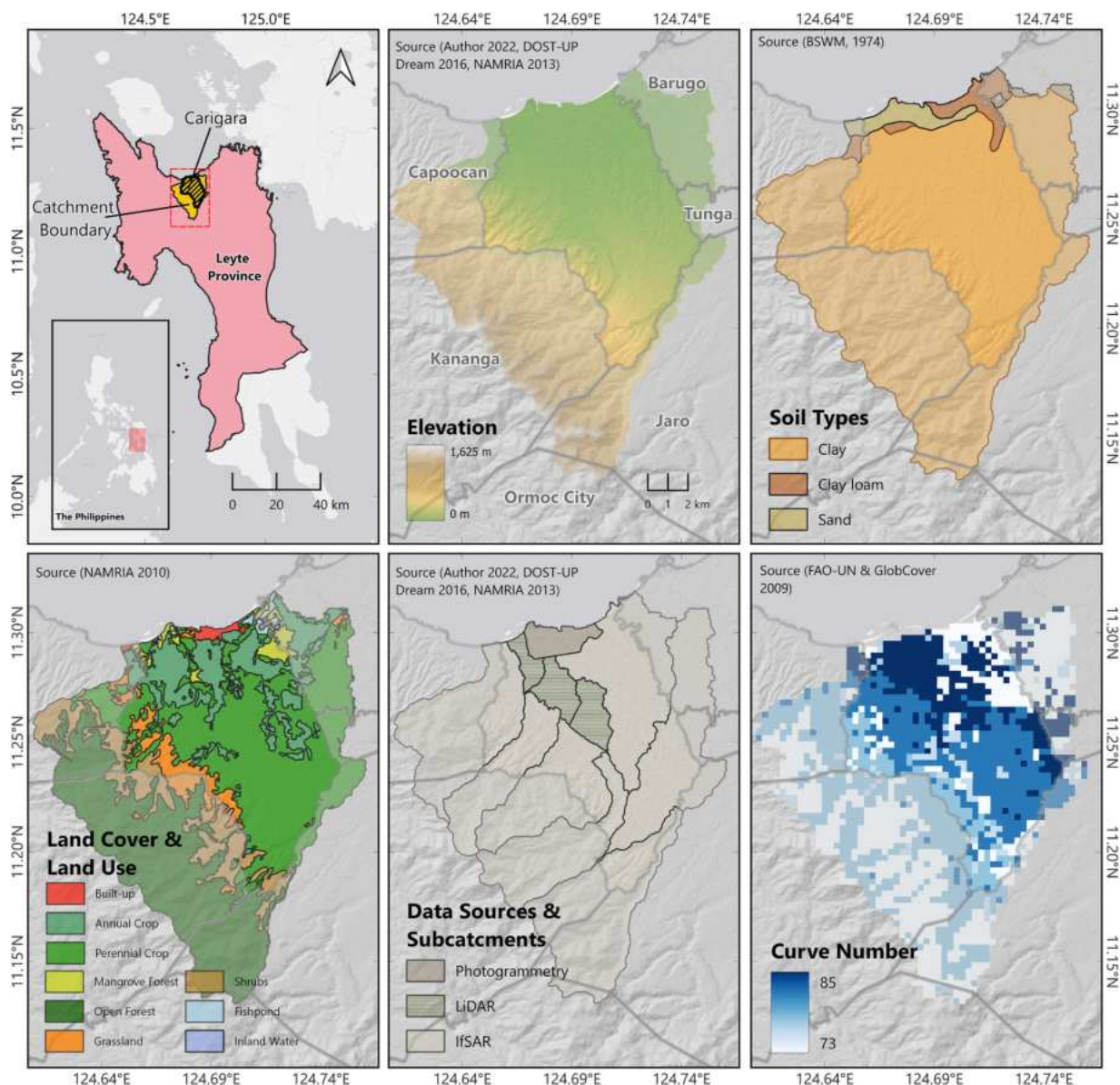


Fig. 2. Flood inputs for flood inundation modelling.

2.2.1.2. Landcover and soil types. Land cover data for this study was extracted from the NAMRIA Landcover dataset 2010, offering a comprehensive overview of Carigara's distribution of land use with the corresponding Manning coefficients (NAMRIA, 2010). This dataset encompassed a variety of land cover categories, including build-up areas (0.04), fishponds/inland water (0.01), mangrove forests (0.32), and annual and perennial crops (0.14) along the coastal regions. In upland areas of the catchment, the dataset covered open forests (0.32), shrubs (0.35) and grassland (0.3). Three main soil types were identified by the Bureau of Soils and Water Management (BSWM) as sand, clay loam, and clay in the upland region (BSWM, 1974). These parameters were then used to derive the curve number, a dimensionless index that indicates the run-off from excess rainfall, soil porosity, and hydraulic conductivity (Cipriano et al., 2015).

2.2.1.3. Rainfall. Rainfall data were derived from 61 synoptic stations that were collected until 2010 by PAGASA, which collects 24-h accumulated rainfall, providing a historical baseline of 5-year, 25-year, 50-year and 100-year (PAGASA, 2010). Subsequently, we used statistical analysis to interpolate across synoptic stations to derive accumulated rainfall, for the Province of Leyte. For this study, we focus on 24-h flood scenarios (Rx1day), consistent with PAGASA flood risk assessments, which are the basis for formulating regulations and designing storm-water management facilities. Peak rainfall was calculated to be 16–24 h. The rainfall data was calculated for the entire Province of Leyte. To ensure alignment with future climate scenarios, we consider a baseline historical scenario and three distinct phases: early-future (2020–2039), middle-future (2046–2065), and late-future (2089–2099) for both RCPs 4.5 and 8.5. These future projections allow us to anticipate the changes in rainfall patterns over time.

2.2.1.4. Climate projections. Global climate models (GCM) utilise numerical representations to show the interactions between the components of climate systems. Regional climate model (RGM) downscale results from GCMs to more localised scales. We use RCMs adopted by DOST-PAGASA, which were developed collaboratively by regional and global institutions, including the Manila Observatory, Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Coordinated Regional Climate Downscaling Experiment (CORDEX-SEA) (Tangang et al., 2020). The downscaling procedures utilise 200-km resolution CMIP5 GCMs as the input for RCMs covering the Southeast Asia region at a 25-km resolution based on three variables: precipitation, minimum and maximum temperature (Basconcello, 2015; DOST-PAGASA et al., 2022). The Intergovernmental Panel on Climate Change (IPCC) compiles climate projection scenarios based on greenhouse gas representative concentration pathways (RCPs) – which include RCP2.6, RCP4.5, RCP6.0 and RCP8.5 – with the latter being high-emission scenario from the Fifth Assessment Report (AR5) (IPCC, 2014). For this study, we focus on RCP 4.5 and 8.5 to understand the outcomes of intermediate mitigation strategies put in place as well as a worst-case scenario.

2.2.2. Residential exposure

This study considered 11,788 residential structures as the exposure units of interest. Previous extensive mapping effort was undertaken by the Barangay Disaster Risk Reduction Management Committees (BDRRMCs) and the LGU in Carigara to digitise all building stock information using OpenStreetMap (OSM) in 2018. Using FieldPapers, an atlas mapping tool, georeferenced maps were printed for community members to add building footprints, which were then cross-checked using satellite imagery, digitised using OSM, and validated through iterative rounds of consultation with BDRRMCs. Since then, the building stock has been routinely updated in consultation with local BDRRMCs to remove abandoned structures or to add new construction. Each building had relevant attributes mapped, including primary wall materials,

which were categorised as (1) concrete/masonry, (2) mixed concrete/masonry and wood, (3) wood, (4) scrap material, and (5) missing data. Structures were also classified by use, with those which are tagged as occupied for residential use as data used for this study.

2.2.3. Residential vulnerability

Residential structure flood damage relationships were drawn from empirically derived vulnerability functions developed to assess structure damage ratio. The damage ratio shows the relationship between flood depths and the degree of damage to structures. These functions were developed for three residential building typologies – (1) concrete structures, (2) light material structures, and (3) elevated light material structures – which formed the foundation of our assessment of physical vulnerability (Besarra et al., 2024). To align building material classifications with descriptions identified by the LGU, those structures classified as 'mixed concrete and wood' construction through local government surveys were modelled using the concrete typology vulnerability functions. This decision was based on the intended use of these functions with reasonable variation in combinations of materials and expected substructure damage when exposed to flooding. Those residential structures classified as entirely wood or scrap material were modelled using the light material vulnerability functions as these again matched the original building sample surveyed when generating the functions.

2.2.4. Cost analysis of construction

Building costs were collected through a workshop with 90 participants in February 2024, including 45 barangay captains (community leaders), 32 Sangguniang Kabataan (youth council members), 6 disaster risk management staff, 2 municipal planning staff, and 5 other stakeholders. Participants were asked to estimate the total cost (inclusive of labour) for the three identified single-story typologies (seen in Fig. 3) for 25 m², 50 m², and 100 m². To further validate these costs, we compared cost values from the workshop with three in-depth interviews with experienced local builders, suppliers, and engineers to derive average costs per square metre for each building typology. The cost of reconstruction per typology was then averaged across responses, resulting in estimates of 7,055 PHP/m² for concrete/masonry structures, 1,945 PHP/m² for light material structures (non-elevated), and 3,028 PHP/m² for elevated light material structures.

2.3. Data analysis

This section outlines the flood modelling process to derive residential risk estimates and project shifts in risk patterns over the next century.

2.3.1. Flood modelling

We used FLO-2D (Flo-2D GDS Pro) software for flood modelling at a 2-m resolution for floodplain and coastal areas, while upland catchments were modelled at a 6-m resolution to match DEM resolutions. Rainfall contours were then developed by interpolating accumulated historical baseline rainfall values from each synoptic station across the country. When creating the final hydrograph, we delineated the catchment boundaries by using a set of tools on ArcMap with the corresponding catchment DEM. Climate change-projected data on shifts in precipitation patterns was obtained from the *Philippine Climate Extremes Report 2020* (DOST-PAGASA et al., 2022). The percentage difference between the climate projected for Rx1day was then applied to the baseline historical rainfall values for the Province of Leyte.

2.3.2. Quantifying shifts in flood risk

The recognition of the adverse impacts of climate change on risk has been a key focus for both national and international policy agendas prompting a strong drive for new knowledge for the development of concrete adaptation actions (Patwardhan et al., 2009). Numerous studies have integrated the impacts of natural hazards and climate change into



Fig. 3. Building typologies identified for localised vulnerability functions. (a) Light material, (b) elevated light material, and (c) concrete structures.

assessments utilising geographic information system (GIS) tools to conduct spatial hazard risk assessments (Espada et al., 2015; Hadipour et al., 2020; Narendr et al., 2022; Wang et al., 2024). In this study when quantifying the shifts in flood risk, we took a household-scale approach to understanding the influence of damages on different construction types. Existing studies assess these shifts in risk at a barangay level (village) through population density, or a percentage of affected built-up area from land use maps across the Philippines (Alfonso et al., 2019; Cabrera and Lee, 2018; Kefi et al., 2020). In contrast, we identify this risk at a more granular building level, which allows for a detailed assessment of how different building typologies are affected by flood events. To account for uncertainties in the building exposure and vulnerability data, Monte Carlo simulations were conducted to capture these uncertainties. Consequently, we graphically represent damage through histograms to capture uncertainty and cumulative distribution functions to estimate the expected damage to structures within the municipality. Finally, we compare projected damage to historical baseline scenarios to understand the direct attributes linked to climate change.

2.3.2.1. Building reclassification. Due to gaps in our data for some building characteristics, we employed a Monte Carlo Analysis (MCA) to randomly distribute these attributes amongst the building stock. In our data, 729 (6 %) residential structures had no designated material classification collected from household surveys. To address this, we randomly sampled ratios between 25 % and 75 % for heavy versus light material structures, assigning individual classifications to buildings within the missing data. For light material structures, we did not have

information on whether structures were elevated. Consequently, we also randomly sampled ratios between 25 % and 75 % of elevated versus non-elevated structures within the light materials classifications. A ratio between 25 % and 75 % assumed that building classifications outside these ranges would be unrealistic. We used 1,000 iterations to assign both above scenarios spatially. This number of iterations was chosen to ensure the robustness and reliability of the building reclassification process. The code of analysis can be seen in [Supplementary Appendix B](#).

2.3.2.2. Risk identification. From 11,788 building footprints, 7,502 structures were reclassified as concrete structures, 3,557 as light material structures (randomly distributed to reclassify as elevated and non-elevated structures), and the remaining 729 were randomly distributed as one of three typologies in the MCA. Calculated damages reflected the reconstruction or repair cost of structures and excluded household assets, such as belongings. We also assumed flood depths below 0.2 m to result in negligible damage.

The spatial point sampling process involved overlaying flood inundation scenarios with building footprints to identify flood depths at the centroid of each building. By pairing each building unit with a corresponding building typology, we then applied our vulnerability functions to identify an expected damage ratio. The estimated floor area of each building was calculated based on OSM building footprints. By combining the damage ratio, flood area of the structure, and cost (per square metre), we were able to estimate the reconstruction cost for individual structures across the municipality. We then estimated housing damages for each period (early, mid and late scenario) under each RCP scenario (4.5 and 8.5).

2.3.2.3. *Flood model validation.* Flood validation points were empirically collected from 39 geotagged locations. We directly measured the recollected inundation depths based on local resident experiences, supported with visible markings where possible on structures. All events were based on Tropical Storm Megi (locally known as Tropical Storm Agaton), which occurred in April 2022. This storm was chosen because it was the most recent significant flood event that local households could recall. During this event, 24-h rainfall of 536.2 mm in Baybay City (the closest weather station point to Carigara) was collected by [DOST-PA-GASA \(2022\)](#), which corresponds to a 100-year historical rainfall return period. To validate our model, we compared the difference in inundation depths collected from Tropical Storm Megi against the historical baseline model. Simulation accuracy was determined by the root mean

square error (RMSE) in Equation to evaluate the performance between observed and simulated values.

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (y_i - \hat{y}_i)^2}{N - 1}} \tag{1}$$

RMSE = Root mean square error
y_i = simulation flood depths results
ŷ_i = observed flood depth
N = number of observation points

Compared to our model, 33 % of validation points had differences ranging between 0.0 m–0.24 m and 45 % had differences ranging

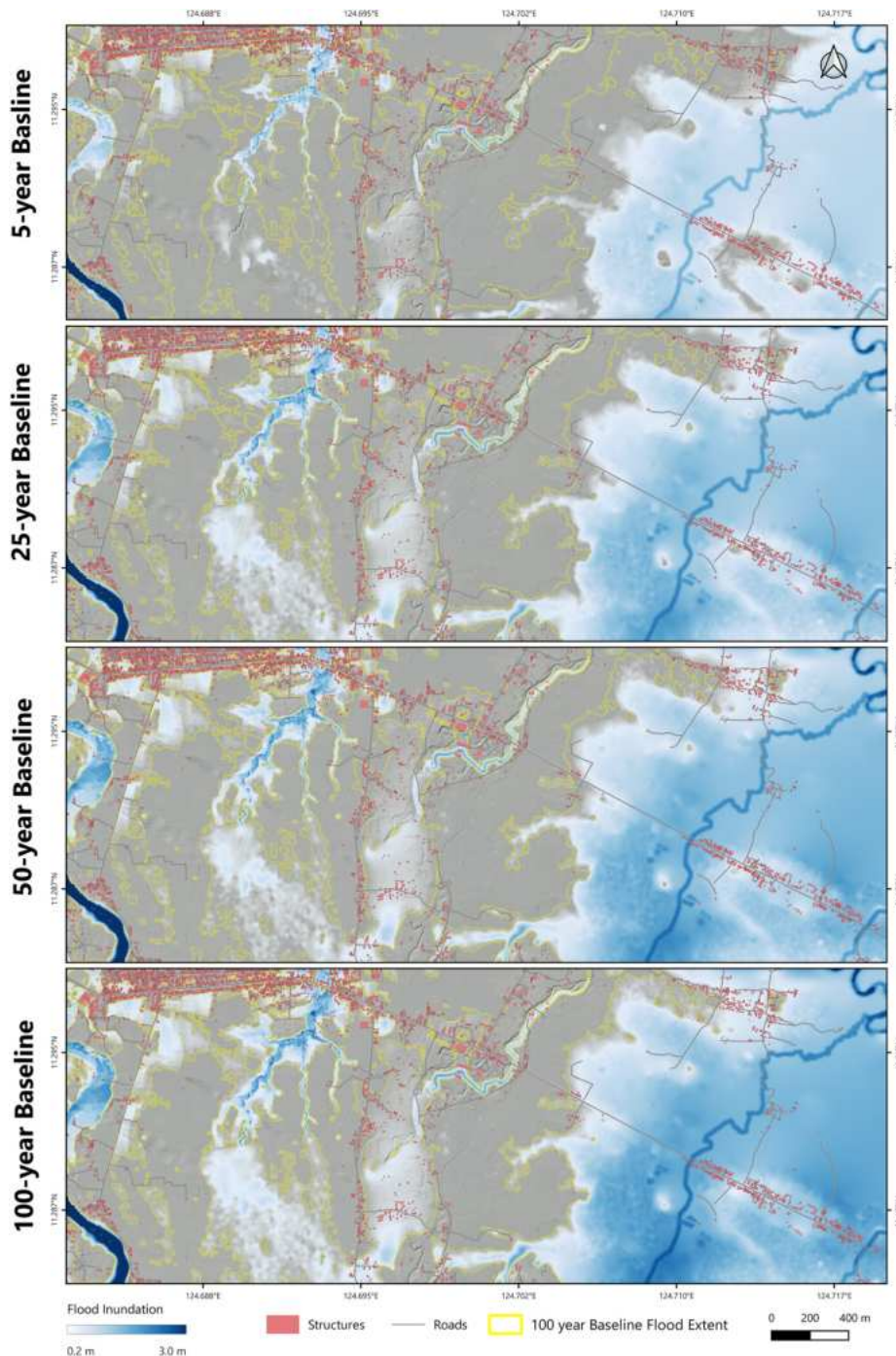


Fig. 4. Flood extents for baseline return periods.

between 0.25m–0.49 m. For 9 % (n = 3) of points, reported differences were greater than 1-m from our model. This could correspond to respondents having to evacuate their residences before the peak flood depth, or lacking experience with extreme events. The RMSE was calculated to be 0.43 m aligning with existing studies as a reasonable level of model error (Alfian et al., 2023; Clasing et al., 2023; Dasallas et al., 2024).

3. Results

In this section, we present the findings on the impacts of climate change on future flood damage. First, our analysis evaluates shifting

patterns in flood risk by examining total municipal-scale housing damages across 24 climate scenarios. In doing so, we compare these climate scenarios against a historical baseline to give insights into the attributable impacts of climate change on flooding. We provide insight through a probabilistic lens and unpack the underlying physical vulnerabilities that may contribute to these cost disparities.

The model results indicate flood extents of 18.3 km², 24.9 km², 26.0 km², and 27.9 km² for 5-, 25-, 50-, and 100-year historical baseline return periods, respectively. These correspond to inundation areas representing 21 %, 30 %, 31 %, 32 % of the total municipal land area. The changes in flood extents and depths across the baseline return periods are depicted in Fig. 4. Under RCP 4.5, 100-year return period events are

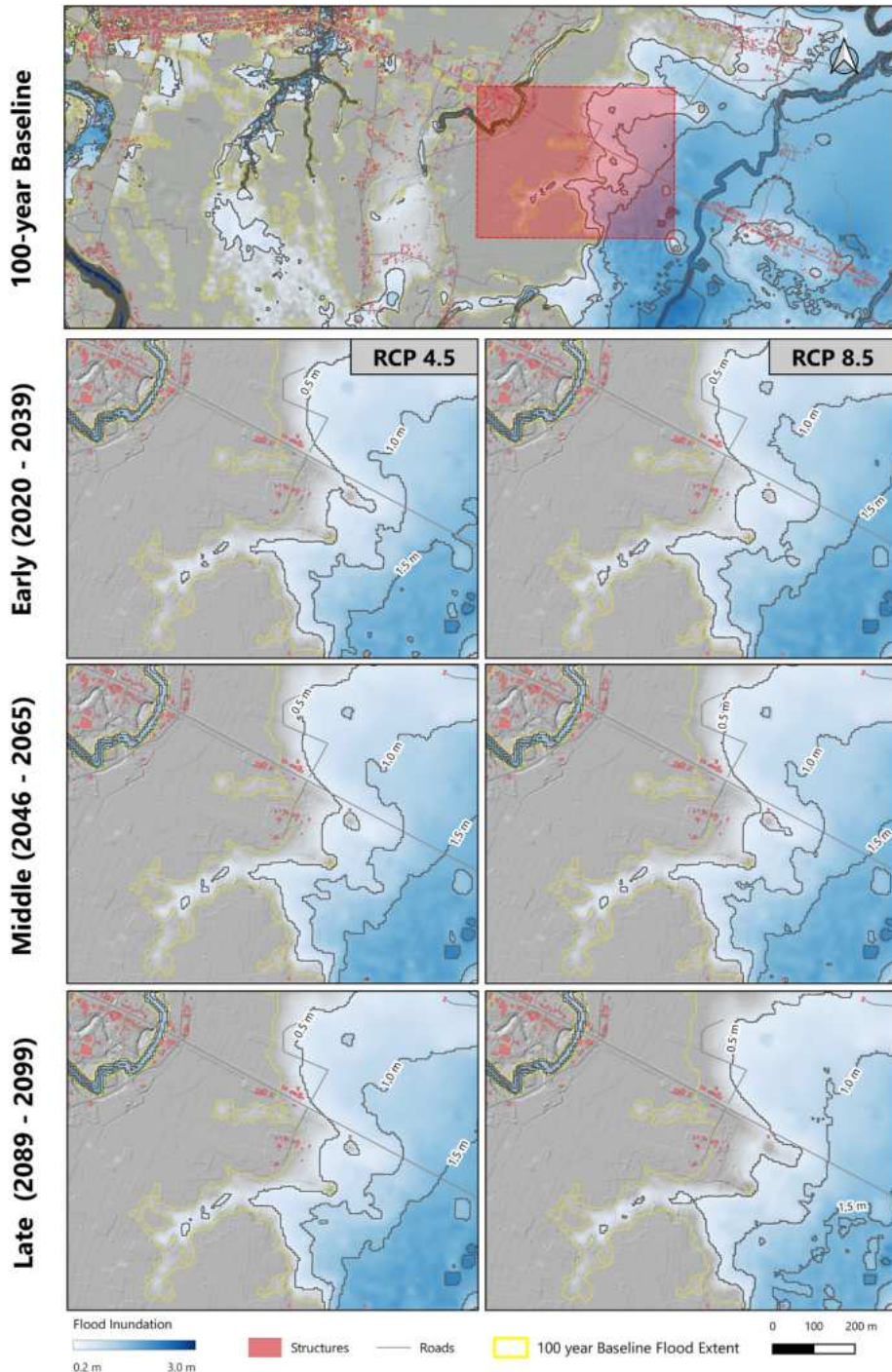


Fig. 5. Shifting flood extents under RCP 4.5 and 8.5 for a 100-year return period.

expected to decrease in extent by 4.6 % in early-term projections and by 0.9 % by the end of the century relative to the baseline, as seen in Fig. 5. Conversely, under RCP 8.5, 100-year return period flood extents will increase by 0.1 % in the early-term and decrease by 8.1 % at the end of the century relative to the baseline. These changes are significant as they show visible receding in flood extents, particularly in the late horizon, which will reduce potential damages to residential structures. The remaining flood hazard maps can be seen in Supplementary Appendix A.

3.1. Municipal scale damage over climate change

Flood risk patterns in RCP 4.5 illustrate damages below the historical baseline across all time horizons. However, short-term declines are expected to return to the existing baseline damages by the end of the century. RCP 8.5 flood damage estimates exhibit an increase for near-term (early) timescales; however, flood damages are expected to decrease by the middle and late timescales. Median damages, and 10th and 90th percentiles, are reported in Table 1. The reported variability stems from assumptions in classifying buildings. In Fig. 6 we illustrate these damages, where the frequency represents the number of considered building stock distributions from the MCA.

The RCP 4.5 emission pathway corresponds to a significant decline in flood risk in the near term, which steadily increases until 2100, albeit with expected damage consistently below the historical baseline values. In the early scenario (2020–2039), our results suggest a 30 % and 21 % decrease in projected flood damage attributable to climate change for 25-year and 100-year return periods, respectively, relative to the baseline. By the mid-term (2046–2065), the probability of damage is projected to increase slightly compared to the near term. However, flood damages are expected to be 15 %–10 % lower compared to the baseline for 50-year and 100-year return period events, respectively. Similarly, under the late-century scenario (2089–2099), 6 % and 3 % decreases across all return period events are expected, highlighting a return closer to baseline damages.

Flood risk trends are mirrored when assessing the RCP 8.5 emission pathways, with the early scenario above current baseline values and significantly decreased damages by 2100. The early scenario exhibits a slight increase in flood damages of 4 % above baseline historical values for a 25-year period – the highest increase of the four considered return periods in the short term. The mid-century scenario projects a sharp decline in losses of between 23 % and 15 % across all four return periods from baseline values. Lastly, the late-century scenario shows the lowest values in total loss and damage to residential structures, with damages declining 44 %–34 % across all considered return periods compared to historical baselines.

For the baseline, the differences between the 10th and 90th percentiles of damage were PHP 79,000, PHP 200,000, PHP 237,000 and PHP 292,000 for 5-year, 25-year, 50-year, and 100-year return periods, respectively. The uncertainty in damages increases for more severe flood events (i.e. 100-year) due to larger extents of inundation. This larger flood extent enabled more building combinations in the MCA

simulation. To further assess the robustness of this analysis we also compared median values of expected damage from the 100-year baseline to account for extreme events in our reclassification processes. This included Case 1: all missing data was defined as concrete, with all existing light material structures non-elevated. Case 2: all missing data was defined as concrete with all existing light materials elevated. Case 3: all missing data was defined as light material, with both newly assigned and existing light materials also non-elevated. Case 4: all missing data was defined as light material with newly assigned and existing light materials being elevated. Analysing all cases showed that the variations in the reclassification altered the total damage cost by ± 2.7 % between MCA simulations, showing low impact on the final reported results.

3.2. Underlying physical vulnerability of damages

In examining the vulnerability of residential structures, different building typologies emerge as damage drivers. In our analysis, we observed consistent trends in the ratio of affected building typologies (e.g. concrete vs timber) across RCPs and time horizons, as seen in Fig. 7. Notably, the ratio of affected structures of concrete houses fluctuated between 61 % and 62 % for the 100-year return period across scenarios. Concrete structures had the highest average building floor area of 128.7 m², compared to light material structures (elevated and non-elevated) of 72.2 m². However, for those homes affected by the 100-year baseline flood inundation extents, the average floor area of a concrete building was 60.0 m² as opposed to 40.7 m² for light material structures. These larger floor areas, in combination with higher material costs, explain higher total damage for this typology.

Under the early-term RCP 4.5 5-year return period, 58 % of the affected structures (experienced depths greater than 0.2 m) were classified as concrete. This remains relatively consistent from 60 % for the 25-year and 61 % for both the 50-year and 100-year return periods. However, for a 5-year return period, only 25 % of the total cost of damages corresponds to concrete structures. This value increases to 40 % for the 25-year return period, 46 % for the 50-year return period and 50 % for the 100-year return period. These results highlight the influence of the vulnerability of the housing typology in explaining the shifts in damage costs. While concrete structures were the most affected in the 5-year scenario, they represent lower damages due to lower vulnerability amidst low inundation. Understanding this nuance is important to accurately represent and explain the extent of potential damages.

Focusing on the RCP 8.5 100-year early scenario provides insight into the implications of different building typologies amidst flood events. Of the 11,788 residential structures, 3485 (30 %) were affected by a flood exceeding 0.2 m. Amongst these, concrete structures account for 62 % of affected structures, while light material structures comprise 33 %, with the remaining 5 % being unclassified. Concrete structures also had larger floor areas – 1.5 greater than their light material counterparts. Despite concrete structures having the lowest expected damage per residential building, averaging PHP 1,500 per building, they incurred higher total damages due to more exposed structures,

Table 1
Total flood damage for municipal scales across historical baselines and 24-climate projected scenarios.

		Flood Return Period			
		5-year	25-year	50-year	100-year
Scenarios	Baseline ^a	1.29 [1.25–1.33]	5.21 [5.11–5.31]	7.06 [6.94–7.18]	9.55 [9.41–9.69]
	RCP 4.5 ^{a,b}				
	Early	0.92 [0.89–0.95] (-29 %) ↓	3.65 [3.56–3.74] (-30 %) ↓	5.46 [5.35–5.57] (-10 %) ↓	7.54 [7.42–7.66] (-21 %) ↓
	Middle	1.11 [1.07–1.14] (-14 %) ↓	4.67 [4.57–4.77] (-10 %) ↓	5.99 [5.87–6.11] (-15 %) ↓	8.62 [8.48–8.75] (-10 %) ↓
	Late	1.22 [1.18–1.25] (-6 %) ↓	5.00 [4.90–5.10] (-4 %) ↓	6.75 [6.63–6.87] (-4 %) ↓	9.24 [9.10–9.38] (-3 %) ↓
	RCP 8.5 ^{a,b}				
	Early	1.30 [1.25–1.33] (<1 %) ↑	5.44 [5.33–5.54] (4 %) ↑	7.14 [7.02–7.27] (1 %) ↑	9.66 [9.53–9.80] (1 %) ↑
	Middle	1.03 [1.00–1.06] (-20 %) ↓	4.03 [3.94–4.12] (-23 %) ↓	6.01 [5.89–6.11] (-15 %) ↓	8.15 [8.01–8.28] (-15 %) ↓
	Late	0.72 [0.70–0.75] (-44 %) ↓	2.98 [2.90–3.05] (-43 %) ↓	4.54 [4.44–4.63] (-36 %) ↓	6.27 [6.15–6.39] (-34 %) ↓

All damages are reflected in PHP millions.

^a Values reported are as follows: Median [10th– 90th Percentile].

^b Values are percentage shifts of median damages relative to the baseline +/- (Shift %).

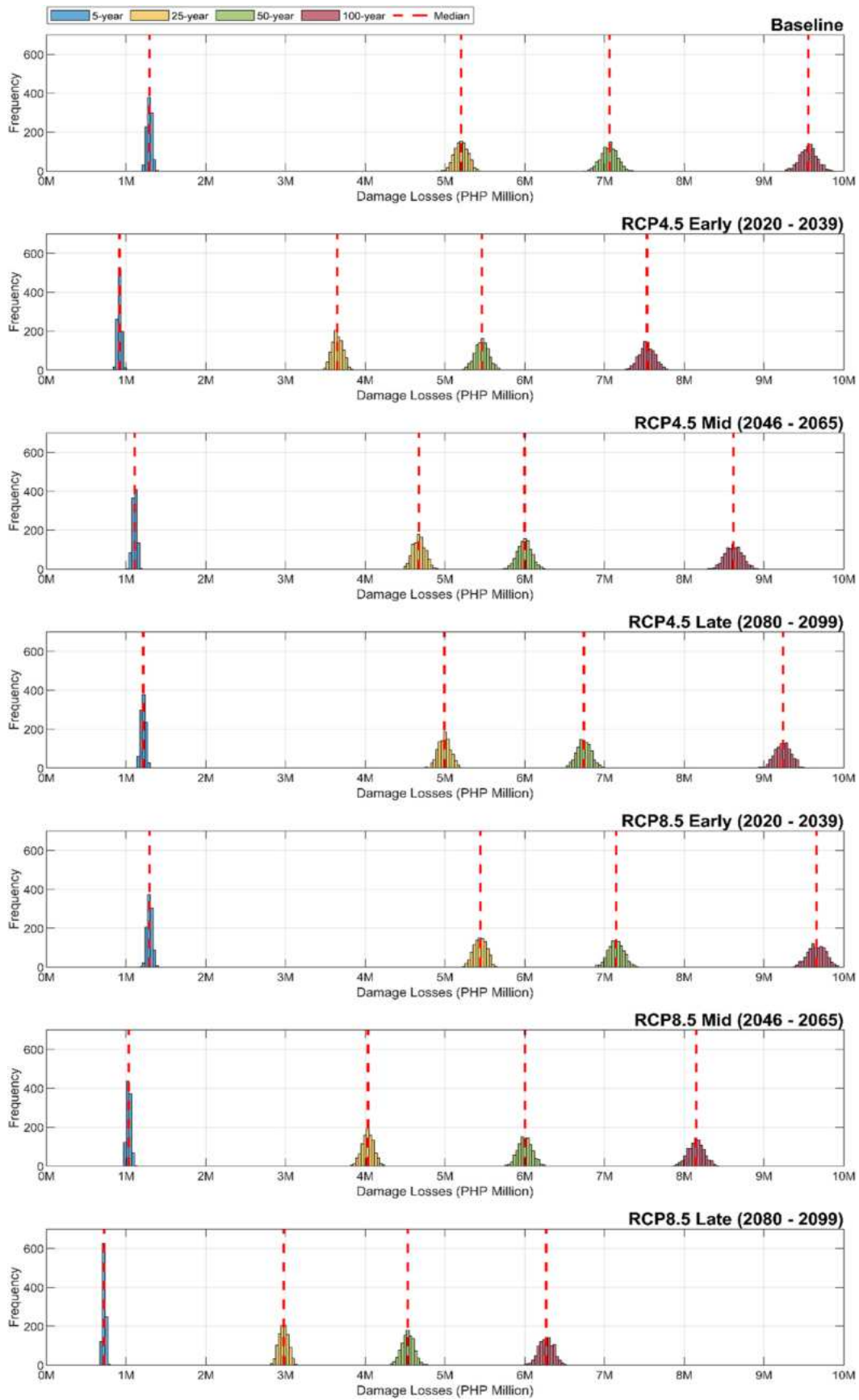


Fig. 6. Distribution of damages across climate scenarios.

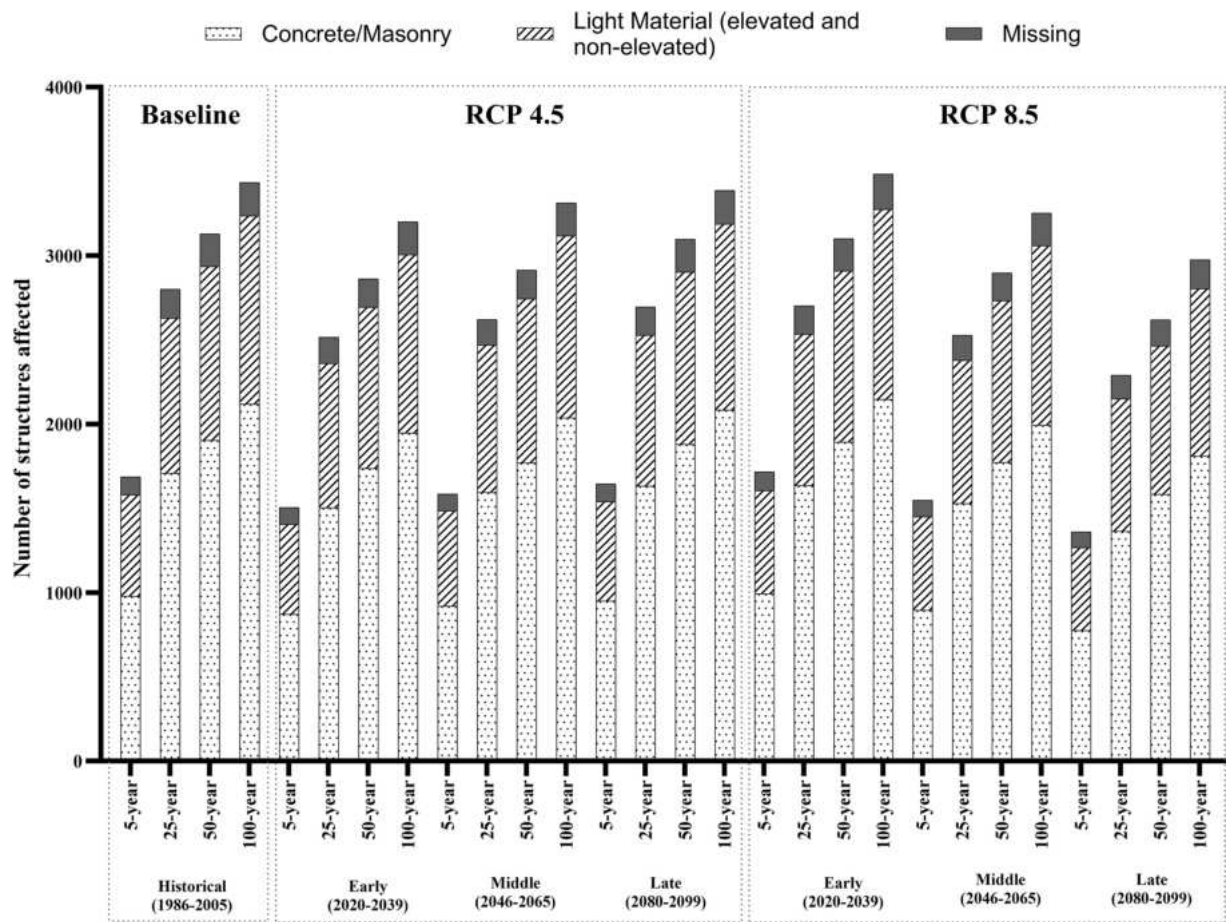


Fig. 7. Number of affected structures across climate scenarios.

amounting to PHP 5.07 million (USD 86,000). In contrast, non-elevated light material structures sustained an average damage of PHP 2560 per structure and total damage across the municipality of PHP 2.20 million (USD 37,500). Lastly, elevated structures had an average of PHP 2,800 damage per structure and total damages of PHP 2.28 million (USD 38,800).

Similarly, under the RCP 8.5 early 100-year scenario, 52 structures experienced inundation greater than 2 m, with 46 % defined as concrete, 48 % as light material (elevated and non-elevated), and 6 % without classification. These affected concrete structures had an average floor size of 57 m² and were, on average, situated 54 m away from major rivers and streams. At 2-m flood depths, these structures were attributed with only a 10 % damage ratio, corresponding to visible yet minor cracks on walls and scouring on floor surfaces (Besarra et al., 2024). Conversely, light material structures that experienced 2-m inundation were at an average distance of 35 m from major waterways, with an expected damage ratio of 30 % (elevated) to 40 % (non-elevated). These damage ratios correspond to sections of houses being washed away or needing significant repairs (ibid). Of the 52 identified structures, 6 result in inundation depths of greater than 3 m and were all classified as light material, having the potential to result in severe damage, such as portions of the structures being washed out, contributing to 6%–9 % of total damages under RCP 8.5.

Despite comprising one-third of all affected structures under the 100-year RCP 8.5 early-term scenario, light material buildings, characterised by smaller floor areas and lower reconstruction costs, account for nearly half of the municipal damages. These damages are attributed to their heightened vulnerability and position distribution along the riverbanks, rendering them particularly susceptible to fluvial flooding. As a result, these structures incur higher damages than their concrete counterparts.

By enabling precision in risk assessments, we can shift from a broad sense of risk to a more detailed understanding of the underlying physical risk factors at the household level. Capturing nuances at household levels allows for effective and targeted disaster planning, highlighting the importance of addressing both the physical characteristics of structures and geographical vulnerabilities in flood-prone areas.

4. Discussion

The impacts of climate change on flood risk are often perceived as uniformly increasing damages (Cea and Costabile, 2022; Hallegatte et al., 2013). However, this study reveals spatial differences and temporal shifts in flood patterns and corresponding damages attributed to climate change. We discuss our findings and unpack how our results can be embedded into local planning processes to advance decision-making. We first look at understanding the importance of climate change attribution and underlying factors that may influence future risk. Then, we examine how our results might inform evolving uses of Local Disaster Risk Reduction and Management Funds (LDRRMF) to support flood response at a local governmental level. From this, we discuss the implications and uncertainties of climate models and implications for ongoing future assessments. We conclude by discussing limitations that can be addressed through future works.

4.1. Communicating climate change risk attribution

Attribution of disaster impacts to climate change is often entangled with other vulnerabilities, making it difficult to establish clear causal links between climate change and damages (Stott et al., 2016). For instance, framing climate change as the sole driver of increasing flood

damages has the potential to overlook underlying risk drivers such as land use planning, physical and socio-economic vulnerability, and urbanisation, which all factor into shaping flood impacts (Birkmann et al., 2022). Although it is important to acknowledge that historical baseline flooding is already severe in many regions, distinguishing the extent to which climate change increases and decreases these extents is crucial for a comprehensive understanding of flood risk planning. This study focuses on a single case site and attempts to capture the dynamics of flood risk by considering types of physical vulnerability and shifts in flood hazards. For instance, under the near-term RCP 4.5 scenario for a 100-year event, we estimate PHP 7.54 million (USD 134,000) in residential damages for building stocks. If we hypothetically consider all structures within Carigara as concrete typologies, these damages would be reduced to PHP 7.11 million (USD 121,000). On the contrary, if all structures were light material structures, this would increase to PHP 11.62 million (USD 198,000) in expected damages. Whilst these results show relatively minor damage reductions for upgrading homes to concrete, alternative flood risk planning could be observed through the construction of flood protection structures and re-zoning of structures out of flood-prone areas. Emphasising that drivers of risk are also contingent on the vulnerabilities and exposure, and not necessarily climate, underscores the importance of future urban growth patterns. Risk attribution of future damage should identify vulnerability as a “starting point” rather than an “endpoint” of climate change (Gumel, 2022).

Understanding these complexities is essential for climate-risk communication strategies. Climate change continues to impact many communities through seasonal shifts in agriculture patterns, prolonged weather events, and impact on livelihoods. While the growth of scientific climate knowledge has advanced significantly, communication to different local government and community stakeholders on potential future impacts has remained a challenge due to varied understanding of risk and levels of awareness (Combest-Friedman et al., 2012; Grefalda et al., 2020). Technical language, probabilistic complexity, and conveying ideas of uncertainty has also played a role in limiting uptake of climate science. Our approach helps make climate information more accessible and actionable.

While other studies from Alfonso et al. (2019), Cabrera and Lee, 2018, and Kefi et al. (2020) determine risk levels at a barangay level or a percentage of built-up land use areas in the Philippines, this study considers risk at the building level through multiple depth-damage functions to distinguish between construction types. By adopting a more granular approach, our research enables further distinction of vulnerabilities at a household level. Commonly, risk labels (e.g. “low-risk area”) in mapping efforts provide broad information on potential impacts across large areas. These generalisations may fall short of enabling informed decisions as they lack specificity regarding the precise underlying drivers and locations of these risks. The push for translating scientific information into digestible application, especially with climate uncertainty, such as direct cost values of physical assets, can provide a proactive approach to streamline science such results in funding allocations and policy frameworks (Cremen et al., 2022; Fakhruddin et al., 2022).

4.2. Entry points for climate risk funding in local policies

The current disaster risk management framework in the Philippines, outlined in Republic Act. 10121, requires at least 5 % of total municipal revenue to be allocated to Local Disaster Risk Management Funds (LDRRMF), which can be used over a five-year period (NDRRMC, DMB, DILG, 2013). For instance, Carigara, classified as a second-class municipality, has a 2020 revenue of 192.2 million (USD 3.30 million) (COA, 2021). Second-class municipalities are one of five classes designated by the Philippines government, corresponding to an LGU annual regular income of PHP 160,000,000–200,000,000. From this total, approximately PHP 9.60 million (USD 164,000) annually is allocated to the

LDRRMF (not accounting for funds that have accrued from the previous five years). Of this allocation, 70 % is in place for support in programmes that can include risk assessments, training on disaster preparedness and response, and provision of emergency services. The remaining 30 % constitutes a Quick Response Fund (QRF), which enables the rapid disbursement of funds only once a state calamity has been declared. While the LDRRMF allocates funds for disaster-related activities, there is no funding framework, guidance, or oversight that accounts for future climate scenarios, and it is generally spent at the discretion of the LGU, in alignment with the Republic Act. 10121 (Qian et al., 2020; Lasco et al., 2008).

Our findings can guide LGU investments by considering return probabilities as thresholds for risk-informed adaptation investments. Framing municipal scale probabilistic damages through different time-frames and climate scenarios ensures sufficient pools of funds are accessible by accounting for projected damages through risk transfer. This provides alternative risk management options for governments where risk avoidance or mitigation efforts cannot be met. Considering the RCP 8.5 early-term scenario (the scenario with the highest rise in damages over the baseline), a 5-year return period flood event is expected to result in PHP 1.30 million (USD 22,000) in damages for residential buildings. While this excludes other possible damage (e.g. agriculture, commercial, and public infrastructure), the residential damages fall within the assigned budget of the LDRRMF allocated for disaster strengthening programmes. However, a 100-year return period event under late-term RCP 8.5 is anticipated to result in PHP 9.66 million (USD 165,000) in damages to residential structures, exceeding annual LDRRMF budgets for preparedness programs.

Taking the assumption that the probability of the flood event remains constant over time, annualised damages for the 100-year events can be calculated to be PHP 95,490, PHP 75,372, and PHP 86,200 a year under RCP 4.5 for early, mid and late-terms. Similarly, these damages are PHP 96,644, PHP 81,462, and PHP 62,552 a year under RCP 8.5. Despite the relatively ‘low’ probability of this event occurring within a given year, the expected damages become more significant when considering compounding probabilities over an extended period: there is a 5 % chance of experiencing a 100-year event over the course of five years and a 51 % chance through the average Filipino lifetime (WHO, 2020). Framed through this probabilistic lens, it becomes evident that the accrual funds over five years through the LDRRMF should be strategically allocated to prepare and respond to such large-scale events. Despite the limitations posed by national-level government funding frameworks, which lack guidance, and provide fixed amounts based on previous years, local governments should strive to incorporate probabilistic risk assessments when preparing for disasters (Qian et al., 2020). This can be realised by taking greater leadership roles in creating better-informed decisions, such as considering the landscape of future building stocks, both spatially and temporally, under climate projected scenarios. Such action has the potential to enhance community resilience and ensure that resources can be used effectively to address the risk posed by climate change, even with constraints of the existing funding mechanisms.

Our findings offer a proactive approach by identifying housing structures that are highly vulnerable to flood damage. This approach can guide decisions on retrofitting light material structures with more durable materials, elevating homes near waterways, or re-zoning areas that are extremely prone to flood hazards. While these investments can be associated with a high upfront cost, the LDRRMFs still remain underutilised nationally due to bureaucratic bottlenecks (Domingo and Manjar, 2021; Oxfam, 2023; Qian et al., 2020). Implementing probabilistic climate-risk assessments could aid local decision-makers and encourage agencies to take proactive actions to reduce the impacts of future disasters by determining annual average damages for decisions (Farahmand et al., 2024). For instance, while 63 % of the building stock in Carigara is of concrete typology, rebuilding the remaining structures to concrete has the potential to reduce future damages by PHP 840,000

(USD 14,000) under the early-term RCP4.5 for 100-year return period events. Although these expected damages represent 9 % of the annual LDRRMF allocation, this information could help LGUs decide whether investing in retrofitting structures is a worthwhile expenditure for future climate impacts.

4.3. Uncertainties in climate models

Flood risk assessments already incorporate uncertainties, but it is crucial that they continue to evolve to adequately address the complex nature of climate change. Common sources of uncertainty often originate from the climate model itself, such as the downscaling process and correctional bias, which makes it difficult to quantify future events (Fadhel et al., 2017; Hawkins and Sutton, 2011; Kaspersen and Halsnæs, 2017; Sunyer et al., 2015). This makes projecting low-frequency, high-intensity extremes at specific locations complex to quantify (Kaspersen and Halsnæs, 2017). Nonetheless, flood risk analysis that considers future climate scenarios and cost assessments, even when highly uncertain, still provides useful estimates for planning for climate change impacts. In this study, we have reported upper and lower boundaries of expected damages under two climate scenarios to highlight the ranges of possible damage outcomes. Based on these outcomes, the findings can assist decision-makers in making informed decisions in pursuit of local resilience. The willingness to invest in these preventive measures (through adaptation or mitigation) is largely dependent on the willingness of decision-makers to tackle long-term risk reduction (Halsnæs et al., 2015; Kaspersen and Halsnæs, 2017; Weitzman, 2011). The potential impacts of climate change, as evident in flood analyses, highlight more informed decision-making processes and serve as a guide in the ongoing effort to mitigate these future flood risks and prevent future loss and damage.

4.4. Limitations and future works

This study, while providing valuable insights into the impacts of climate change on housing, had several limitations. One limitation was missing building materials and construction attributes for some structures, such as the number of floors and the height of elevated structures. This data was not available in the selected case site. Moreover, this research omitted analysis of coastal flooding, such as storm surges given insufficient data. This study also was limited to the replacement cost of the residential structures, without considering damages associated with personal belongings and non-tangible losses. Including both coastal flooding and losses associated with personal belongings would provide a more comprehensive flood assessment. While this study provides insight into the potential application of climate-informed fund allocation, further study should assess the feasibility of operationalisation in existing national frameworks across varying LGUs.

This research takes an initial step to quantify climate-projected damages in local risk assessments. Future work could extend to understanding the impacts of climate change on other hazards, cascading impacts of disasters, and incorporating new global climate models and methods, including the use of remote sensing data. Another potential area of exploration is the incorporation of models that consider population and urban growth patterns, which could provide more comprehensive insights into understanding future flood risk. Lastly, future works could integrate future climate scenarios that consider social integrations to capture underlying vulnerabilities beyond physical attributes. For instance, combining models with the Shared Socioeconomic Pathways (SSPs) or capturing social dimensions such as household characteristics (age, gender, economic status, etc) could offer a holistic perspective of marginalised groups that may be affected in future scenarios.

5. Conclusion

This study quantified damages to residential structures under 24-climate scenarios, offering insights into how climate change is shifting local flood risk and the implications for households. Our findings show that under an RCP 4.5 pathway, expected future housing flood damages are likely to be below historical baselines for early- and mid-term time horizons; however, these damages are likely to return to near the baseline by the end of the century. In the RCP 8.5 pathway, flood risk for residential structures largely matches the historical baseline for the early term; however, damages are expected to decrease in the mid and late term. While projected flood extent and inundation overall decrease below historical baselines throughout climate scenarios, vulnerability factors such as housing material should not be overlooked during decision making processes when mitigating flood risk impacts. Regardless of scenarios, flood risk remains in Carigara, and while there are ongoing efforts to mitigate the anthropogenic attribution of climate change nationally and globally, there are still proactive measures local governments can implement to minimise their expected future damages.

This study quantified potential damage to better support LGUs in developing effective and localised disaster risk management strategies by simulating future climate scenarios for residential households. These results can enable informed decisions through the utilisation of LDRRMFs for targeted resource allocations. This study contributes to a larger conversation with discussion now focusing on quantifying and attributing damage to climate change impacts. Future work could build upon existing climate-risk modelling to assess additional dynamic factors such as urban growth patterns and multi-hazard events to capture complexities of underlying risk drivers. On a national level, understanding factors that prevent streamlined allocation of disaster-related funds to local governments is crucial for effective and timely disaster response strategies. This research advocates for a proactive approach in response to climate change, promoting strategies for communities rather than viewing climate change as the main driver of risk.

CRediT authorship contribution statement

Isaac Besarra: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aaron Opdyke:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Jerico E. Mendoza:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Patricia Anne Delmendo:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Joy Santiago:** Writing – review & editing, Investigation. **Dino John Evangelista:** Validation, Investigation. **Alfredo Mahar Francisco A. Lagmay:** Writing – review & editing, Supervision.

Declaration of competing interest

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

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Appendix A and B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2025.124966>.

Data availability

Data will be made available on request.

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