MCII

MODELLING FLOOD RISK IN CENTRAL VIET NAM

A Quantitative Assessment of Adaptation Benefits in the Huong River Catchment

FLOOD ADAPT VN

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1.

INTRODUCTION

Viet Nam's extensive coastline and densely populated riverine and coastal regions render it particularly susceptible to flood hazards. The centrally governed city of Hue, formerly part of Thua-Thien Hue province, exemplifies this vulnerability. The Huong River catchment, integral to Hue's urban and peri-urban landscapes, frequently experiences flooding events that adversely affect communities, infrastructure and ecosystems, and thus serves as the research area of this analysis (Figure 1).

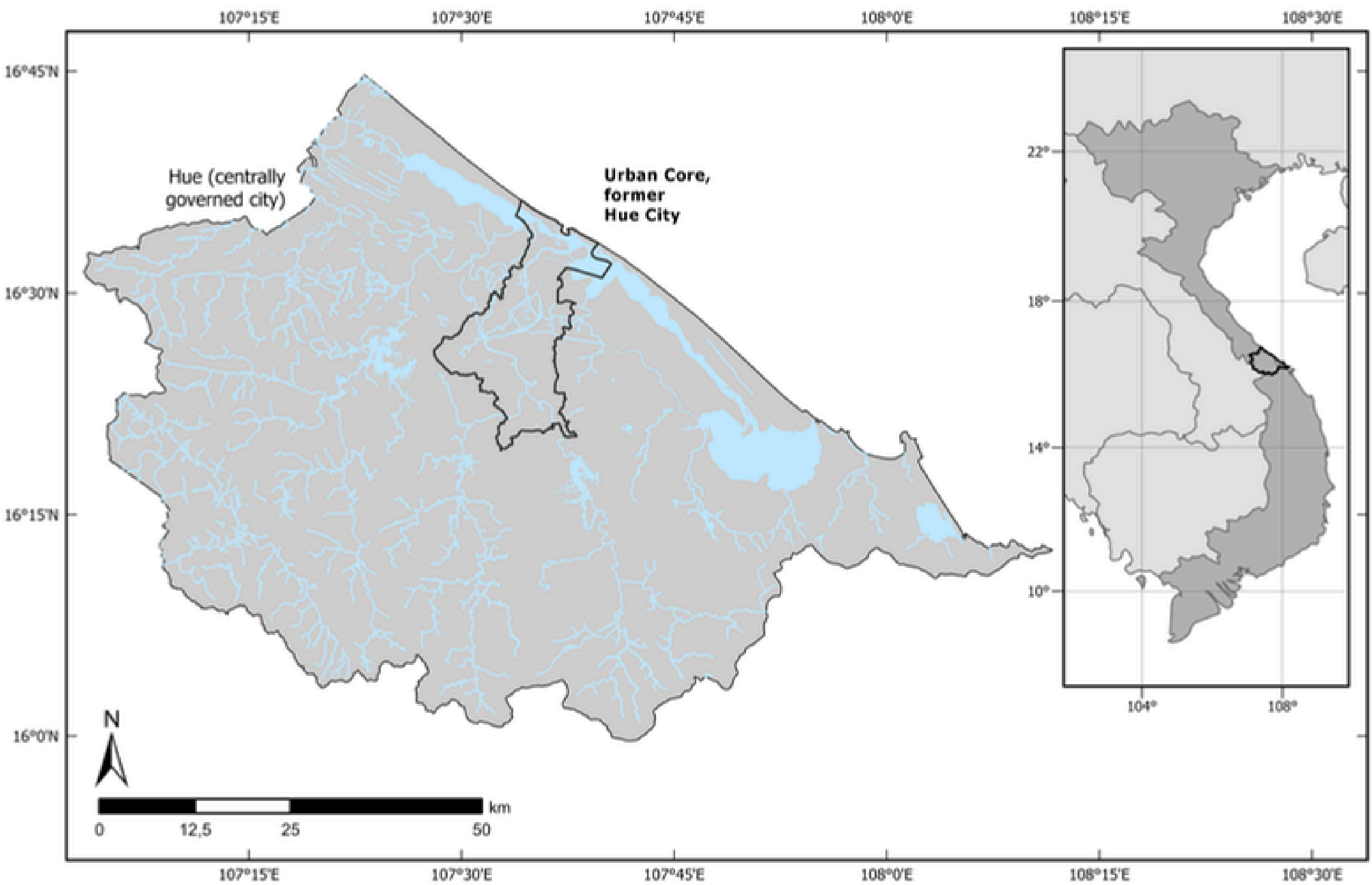

Figure 1: Urban core of Hue: Our research area.

As part of the Research and Development phase of the FloodAdaptVN project—funded by the German Federal Ministry of Education and Research (BMBF) under the "Sustainable Development of Urban Regions" initiative—the consortium members collaborated closely to enhance flood risk assessments toward enhanced flood resilience. A key focus was the evaluation of targeted adaptation strategies, particularly, ecosystem-based adaptation strategies and their integration into local flood risk management for adaptive and sustainable urban development in Central Viet Nam, especially in the city of Hue and the surrounding Huong River catchment. Specific objectives included understanding flood risk drivers, assessing spatial patterns and dynamics, and developing decision support tools for risk-informed spatial planning.

A cornerstone of the project was the valuation and the assessment of flood impacts on people, infrastructure, as well as ecosystems (incl. their services). To gain a more comprehensive picture, the project team applied multiple methodologies, including household surveys covering a broad range of flood-risk-related questions, and workshops with government agencies, academia and communities. These empirical insights – complementing academic literature reviews and official reports –informed the further development of the targeted Economics of Climate Adaptation Viet Nam (ECA-VN) framework and serve as key inputs for the employed quantitative modelling platform CLIMADA.

This report provides a quantitative perspective on flood risks in the Huong River catchment, utilizing the open-source CLIMADA modelling platform to model hazard, exposure and vulnerability data, as well as a specifically developed random forest model, e.g. for building classification. It complements the assessment detailed in the report Flood Risks in Hue, Central Viet Nam: An assessment of flood hazards, exposures, vulnerabilities, root causes and impacts (Sett et al. 2025). Together, these analyses, as well as other outcomes of the FloodAdaptVN project, offer a comprehensive understanding of flood risk dynamics in the region, supporting the development of targeted, sustainable flood risk management and adaptation strategies at the catchment level.

The analysis utilizes the targeted ECA-VN framework, which combines probabilistic risk modelling with cost-benefit analysis to evaluate and prioritize adaptation measures. Distinct innovations of the ECA-VN framework include, for instance, the application of a random forest model to estimate building types (see Chapter 4.2.1) or its participatory modelling process. The newly strengthened participative character emphasizes continuous stakeholder engagement and validation. Local stakeholders, including community members, government officials and academic institutions, are actively involved throughout the process, from identifying key concerns and defining adaptation options to reviewing and refining modelling outcomes. This participatory dimension enhances the relevance, credibility, and uptake of the analysis, ensuring it responds to local priorities and knowledge.

This report contributes to the broader objectives of FloodAdaptVN by providing quantitative insights into flood risk dynamics and informing the development of integrated, sustainable adaptation strategies for Hue and the Huong River catchment.

Building upon this foundation, the report aims to address the following key questions:

1. Which assets and which areas within the Huong River catchment are most at risk from current and projected flood events?
2. What are the potential economic impacts of these flood risks on local communities and infrastructure?
3. How effective and cost-efficient are various adaptation measures, particularly ecosystem-based approaches, in mitigating these risks?
4. How can stakeholder engagement and participatory modelling enhance the relevance and applicability of flood risk assessments in local decision-making processes?

By answering these questions, the report delivers quantitative results and practical recommendations to guide inclusive, sustainable flood risk management in Hue.

To achieve this, chapters 2 - 4 of the report introduce the applied methodology, namely CLIMADA, and the required input parameters, such as assets, the hazard model, damage functions and the chosen adaptation measures. Chapter 5 provides an overview of the results, as the brunt of the results are available on the FRAME platform[1] in order to limit the extent of this report. The final chapter (6) draws conclusions based on the quantitative results and provides first recommendations.

[1] The FRAME Platform can be accessed at https://framefavn.org (DLR/EOC FloodAdaptVN Consortium) (DLR/EOC FloodAdaptVN Consortium).

2.

DATA & METHODOLOGY

To support a robust quantitative flood risk assessment in Hue and the Huong River catchment, we first describe the data sources and processing steps, followed by the methodology applied via the probabilistic modelling platform CLIMADA.

2.1 DATA

2.1.1 Flood Hazard Data

River flood hazard maps for the Huong River catchment were produced using an integrated hydrologic–hydraulic modelling chain, employing the open-source HEC-HMS (v4.11) and HEC-RAS (v6.5) software (U.S. Army Corps of Engineers, Hydrologic Engineering Center 2023, 2024)). Three representative historical flood events—using the classification of the Vietnamese General Department of Hydrometeorology, categorized as historic (15 Oct–14 Nov 1999), exceptionally large (06 Oct–20 Nov 2020) and major (01 Oct–30 Nov 2022)—were simulated to estimate inundation extents under present conditions. Key inputs included:

Digital Elevation and Land Cover: A 30 m Copernicus DEM and 30 m JAXA land-use/land-cover maps, corresponding SCS Curve Number parameters, the derived canopy storage, and flood plain and channel roughness (Manning's n) values.

Hydro-Meteorological Data: Daily/hourly precipitation from provincial gauge networks (interpolated via inverse distance) and tidal stage time series; reservoir elevation–storage curves and management rules (Decision 1606/QĐ-TTg) were applied at Huong Dien, Ta Trach, and Binh Dien reservoirs.

Model Parameterization: HEC-HMS basin models were configured with SCS-CN loss and ModClark routing; HEC-RAS employed a 2D floodplain mesh for lowland areas, incorporating flow inputs from the hydrologic model and sea level boundary conditions.

Validation relied on satellite-derived flood masks (Sentinel-1, RADARSAT, TerraSAR-X) due to sparse in situ gauge records; simulated extents were compared against observed inundations outside urban areas.

Scenario Integration in Hazard Modelling: To capture both climate and socio-economic developments—particularly urban growth—the global Shared Socioeconomic Pathways (SSPs) were downscaled to the provincial level for Hue. Expert consultations and stakeholder workshops adapted the global narratives (SSP1: Sustainability; SSP2: Middle of the Road; SSP3: Regional Rivalry) into locally grounded storylines and quantified assumptions, including projected urban growth for 2050. Flood hazard projections were then extended using four representative RCP–SSP combinations:

- RCP4.5–SSP1: Medium emissions, sustainable development pathway
- RCP4.5–SSP2: Medium emissions, moderate development pathway
- RCP8.5–SSP2: High emissions, moderate development pathway
- RCP8.5–SSP3: High emissions, fragmented regional development pathway

These scenario-based inputs informed changes in precipitation patterns, land cover and boundary conditions for both HEC-HMS and HEC-RAS models, ensuring that hazard maps reflect plausible future conditions. (Obaitor and et al. Submitted; Büche et al. 2025)

2.1.2 Exposure Data

Exposure refers to the spatial distribution and value of assets that are potentially affected by the hazard (Aznar-Siguan and Bresch 2019). This includes buildings, infrastructure, and population. In this study, building footprints and estimated asset values were used as proxies for physical exposure.

For infrastructural assets, such as buildings, road and rail networks, or electrical substations, this analysis relies largely on OpenStreetMap data (Geofabrik 2024), complemented by a field-based building survey conducted in collaboration with consortium partners in 2023 and 2024, capturing details on building characteristics such as usage, height or conditions. Additional optical and radar mosaics were generated in SEPAL (Food and Agriculture Organization of the United Nations 2024) over our study area.[1] Digital elevation data at a 90-meter resolution (TanDEM-X 90m) were obtained from the German Aerospace Center (2020) as further model input.

For agriculture, as non-infrastructural assets, land cover data were provided by the Japan Aerospace Exploration Agency(2021) at a 30-meter grid resolution (agriculture). Aquaculture assets are based on Nieskens and Bachofer (2021).

For the monetary evaluation of infrastructural assets, i.e. buildings of different types, road and rail infrastructure and electrical substations, the specifications as outlined by the Ministry of Construction(1/20/2021) were applied to the different identified asset types and dimensions. In order to retain a reasonably high level of detail for larger structures, such as roads and railways, these were divided into smaller pieces (e.g. strips of approximately 100m). The values for agriculture and aquaculture products are sourced through literature review (e.g. Belton et al. 2011, FAO 2024, Boonstra and Hanh 2015 and the Statistical Year Book by the Hue Statistics Office (2022)).

Exposed people are mapped using subnational population data at a 100-meter resolution provided by Carioli et al. (2023) and the Hue Statistics Office (2022). The population was randomly distributed among the residential buildings following a zero-truncated Poisson[2] distribution using the respective ward's average household size (Jarosz 2021). To classify the residential buildings among all building footprints, a random forest model (Breiman 2001), which incorporates the above-listed data (see Methodologies), was employed. For multifamily buildings, an average apartment size of 90 m^2 was assumed (based on Decision Number: 65 QD-BXD of the Ministry of Construction(1/20/2021)).

The final list of assets is shown in Table 1.

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[2] The study area was defined as 15.994234–16.746663 ° N; 107.055107–108.211778 ° E; EPSG:4326. Optical: Sentinel-2 L2A surface-reflectance imagery (COPERNICUS/S2_SR) from 1 Jan 2023 to 31 Dec 2023 was composited with the default optical_mosaic recipe (cloud_masking = true; max_cloud_cover = 20%), producing a 30 m (0.0000898315°) grid of Blue, Green, Red, NIR, NDVI, EVI, Brightness, Wetness, and Greenness indices (12 876 × 8 376 px; Int16). Radar: Sentinel-1 GRD imagery (COPERNICUS/S1_GRD) over the same period was mosaicked with the default radar_mosaic recipe, yielding a 15 m (0.0001347473°) grid of VH and VV metrics (amplitude, mean, median, max, min, coefficient of variation, phase, residual, standard deviation, texture; 8 584 × 5 584 px; Float32). All outputs (GeoTIFF/VRT) were exported on 12 Jan 2024 (optical) and 16 Jan 2024 (radar).

[3] The Poisson distribution, differing from e.g. a Normal distribution, is typically left skewed with low means as is the case here with means ranging between 2.7 and 4.2 This means the distribution seems to be pushed toward zero with a longer tail to the right, i.e. high values, and is hence not symmetric. This characteristic is well suited to describe household sizes if 0 values are being omitted, i.e. if no households, with no household members, are allowed in the distribution.

Table 1: Selected Asset Clusters and Types

CLUSTER	ASSET TYPE
Infrastructure	
	Residential Buildings
	Road & Rail Infrastructure
	Electrical Substation
	Public Administration/ Offices
	Health & Education Facilities
	Hospitality
	Markets/ Malls
Ecosystem	
	Rice Paddies
	Tree Crops
	Other Crops (legumes, maize, sweet potato, etc.)
	Earth Pond Aquaculture
	Net/Bamboo Stake Ponds
	Net-Enclosures
Population	
	People

In order to reflect intertemporal development, both economic and population growth, assumptions about mean rates were set, and uncertainty intervals were included in the quantitative modelling process. For economic growth, a mean growth rate of 7.52% was assumed (Government of Viet Nam 2023, 2022). An average population growth of 1.38% was assumed following the Government of Viet Nam (2023). Based on approximations of the Economist Intelligence Unit(2024).

2.1.3 Adaptation Measures

For the evaluation of adaptation measures, a short list of adaptation measures to be quantitatively evaluated was derived throughout the project (Sett et al. 2025; Ortiz Vargas et al. 2025). The final list, incl. which assets they target in which parts of the catchment, can be found in Table 2.

Table 2: Overview of Assessed Adaptation Measures and Targeted Asset Types.

NAME OF MEASURE	Type of Measure	Location	Intended Impact Zones	Targeted Assets	Estimated Cost in bn VND (incl. implementation and maintenance)	Estimated Cost in M USD 2025 (incl. implementation and maintenance)
Housing modifications (dry flood-proofing)	Structural	Urban	Urban	Buildings, People	713.8	27.3
Early warning system (watershed level)	Structural	All	All	Agriculture (all crops), Aquaculture, Buildings, People, Road & Rail Infrastructure, Electrical Substations	17.6	0.68
Crop insurance	Institutional	Coast & peri-urban (up- and downstream)	Coast & peri-urban (up- and downstream)	Agriculture (all crops), People	1.9	0.07
Flood risk awareness campaigns	Social	Urban	Urban	People	29.6	1.1
Agroforestry in riparian buffers	EbA	Peri-urban (downstream)	Peri-urban (downstream), Urban	Agriculture (all crops), Aquaculture, Buildings, People, Road & Rail Infrastructure, Electrical Substations	80.3	3.1
Sustainable forest management	EbA	Upstream	Peri-urban (up- and downstream)	Agriculture (all crops), Aquaculture, Buildings, People, Road & Rail Infrastructure, Electrical Substations	13	0.5
Climate smart agriculture	EbA	Coast & peri-urban (up- and downstream)	Coast & peri-urban (up- and downstream)	Agriculture (all crops), People	203.1	7.7
Restoration of natural urban waterbodies	EbA	Urban	Urban, Peri-urban downstream	Buildings, People, Road & Rail Infrastructure, Electrical Substations	10.5	0.4
Mangroves	EbA	Coast	Coast	Agriculture (all crops), People	34.7	1.3
Sum					**1 104.5**	**42.2**

2.2 METHODOLOGY

2.2.1 CLIMADA Modelling Framework

To assess current and future flood risk in the Huong River catchment and the city of Hue, this analysis employs the CLIMADA (CLIMate ADAptation) platform, an open-source, probabilistic modelling framework designed to quantify the impacts of climate-related hazards and evaluate the benefits of adaptation measures (Aznar-Siguan and Bresch 2019; Bresch and Aznar-Siguan 2020). CLIMADA follows a modular structure comprising four core components: Hazard, Exposure, Vulnerability and Adaptation. It utilizes the data described above and relies on the building classification outcomes.

By integrating these modules, CLIMADA produces key indicators such as Expected Annual Impacts (EAI), risk maps and benefit–cost ratios, enabling comparison of adaptation options under multiple climate and socio-economic scenarios.

2.2.2 Vulnerability Modelling

For the probabilistic modelling approach, vulnerability is expressed in so-called vulnerability functions, also called damage or impact functions. Vulnerability functions describe the relationship between hazard intensity—such as flood depth—and the expected level of damage to an asset or group of assets. (Aznar-Siguan and Bresch 2019). The correct definition of these functions is critical for producing realistic impact estimates.

A hybrid approach was applied to construct the vulnerability functions used in this study. As a starting point, generic damage functions were taken from the Joint Research Centre's (JRC) global flood depth-damage functions (Moel et al. 2016) and from a similar application in Can Tho, Viet Nam (Behre et al. 2021).

These generic curves were cross-referenced and then calibrated using locally specific information obtained from several district-level flood damage reports, primarily Hue, covering floods in the period between 2003 and 2022, which systematically document impacts on people and a wide range of infrastructure, as well as agriculture and aquaculture. These reports were used to adjust the slope and thresholds of the vulnerability functions in order to better reflect real conditions in Hue and the Huong River catchment. Due to the limited number of systematic in-situ records, the calibration process was supported by local expert input gathered through stakeholder consultations.

2.2.3 Building Classification Using a Random Forest Model

Building type is key to understanding flood impacts at a granular level and a core input of the probabilistic CLIMADA modelling platform employed for the impact and adaptation assessment. Therefore, a two-stage Random Forest workflow that classifies each footprint into vulnerability-relevant categories was applied.

Analyses were conducted in Python 3.11.7 with scikit-learn 1.0.2 (Pedregosa et al. 2011) and Optuna 3.4.0 (Akiba et al. 2019). To ensure reproducibility, a fixed random_state=42 was set for both the train-validation split and the RandomForestClassifier.

Stage 1: Primary Category Classification implemented a Random Forest model to assign each building footprint to one of thirteen functional types—ranging from residential and educational facilities to industrial sites, markets, offices and cultural venues. This classification combined detailed field-survey attributes (such as roof materials, number of stories, and usage) with remotely sensed predictors (including elevation, footprint area, proximity to roads, local building density in buffer zones and radar/optical indices). Hyperparameters (number of trees, tree depth, split and leaf sizes, feature selection and criterion) were optimized using Optuna (Akiba et al. 2019) over 2,000 trials, maximizing weighted precision on an 80/20 train–validation split.

Stage 2: Residential Typology Refinement focused exclusively on those footprints labeled “residential” in Stage 1. Applying the same feature set and Random Forest architecture, this second model distinguished single-family from multi-family dwellings, addressing class imbalance and achieving finer granularity in exposure assessment.

In both stages, missing data were imputed with SimpleImputer, categorical variables were encoded with LabelEncoder, and continuous predictors were standardized with StandardScaler[4]. The combined workflow was trained on 5,382 labeled samples (Stage 1) and the residential subset (~75% of Stage 1; Stage 2), ultimately classifying approximately 114,988 footprints across the Huong River catchment. Model performance was evaluated on a held-out validation set (n=1 077), where it achieved 91% overall accuracy, with weighted precision, recall and F1-score all at 0.91. Per-class recall ranged from 28% (smallest class) up to 98% (largest class), reflecting natural imbalances in urban building types. The top five predictors (the building’s footprint size, the ward-level population density, the distance to major roads, the highway, and to small residential roads and paths) accounted for more than a quarter of the model’s decision power. Full scripts and performance diagnostics are available upon request.

2.2.4 Participatory Modelling Approach

The ECA-VN application of CLIMADA was underpinned by an inclusive, stakeholder-driven modelling process (Figure 2), ensuring the analysis remained locally relevant and transparent. Local authorities, academia, civil society and national agencies collaborated to:

- Define Scenarios: Adapt global RCP–SSP narratives (SSP1, SSP2, SSP3) to the provincial context, including 2050 urban growth projections.
- Validate Data and Assumptions: Review asset inventories, valuation methods and depth–damage functions.
- Select and Calibrate Measures: Identify locally feasible adaptation options and fine-tune their cost, effectiveness and lifespan parameters.

This participatory approach not only enriched the inputs for CLIMADA’s Hazard, Exposure, Vulnerability and Adaptation modules, but also guided the Adaptation Benefit–Cost Analysis under four RCP–SSP scenarios (RCP4.5–SSP1; RCP4.5–SSP2; RCP8.5–SSP2; RCP8.5–SSP3), resulting in tailored, credible recommendations.

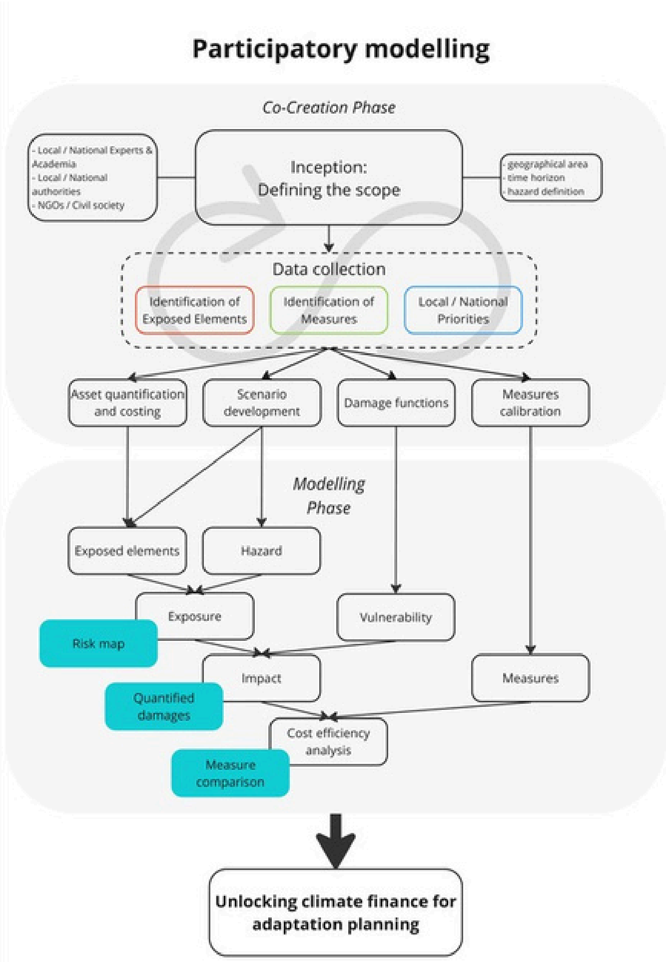


Figure 2: Participatory Modelling Approach for ECA-VN

[4] Imputation ensures that no missing values break the model fitting. Encoding turn text or categorical labels into numeric codes the classifier can work with. Standardization puts all continuous inputs on a common scale. These preprocessing transformers are components of the scikit-learn 1.0.2 library (Pedregosa et al. 2011).

3.

RESULTS

To support a robust quantitative flood risk assessment in Hue and the Huong River catchment, we first describe the data sources and processing steps, followed by the methodology applied via the probabilistic modelling platform CLIMADA.

3.1 EXPECTED ANNUAL IMPACT (PRESENT & FUTURE)

This section presents the overall quantified flood risk results for Hue and the Huong River catchment, summarizing the total expected annual impact across all considered asset categories under current and future climate scenarios. The following graphs in Figure 3 showcase today's expected annual risk or impact in blue. They further show the expected increase due to economic development and climate change, and the resulting expected annual risk in 2050. The whiskers on each bar (except today's baseline) denote the 90% uncertainty interval (5th - 95th percentile) from a bootstrapped ensemble: by repeatedly re-sampling hazard, exposure, and vulnerability inputs, we build a distribution of possible annual impacts, and the whiskers bound its central 90%.

While today's expected annual risk, or impact, is estimated at around VND 772.2 billion, this is expected to increase up to around VND 3,200 billion and VND 5,300 billion respectively by 2050 under the four considered RCP-SSP scenarios (Figure 3 a): RCP4.5-SSP1, b): RCP4.5-SSP2, c): RCP8.5-SSP2, d): RCP8.5-SSP3). These numbers especially highlight the stark increase expected in terms of climate change effects between the moderate RCP4.5 and the extreme RCP8.5 climate scenario.

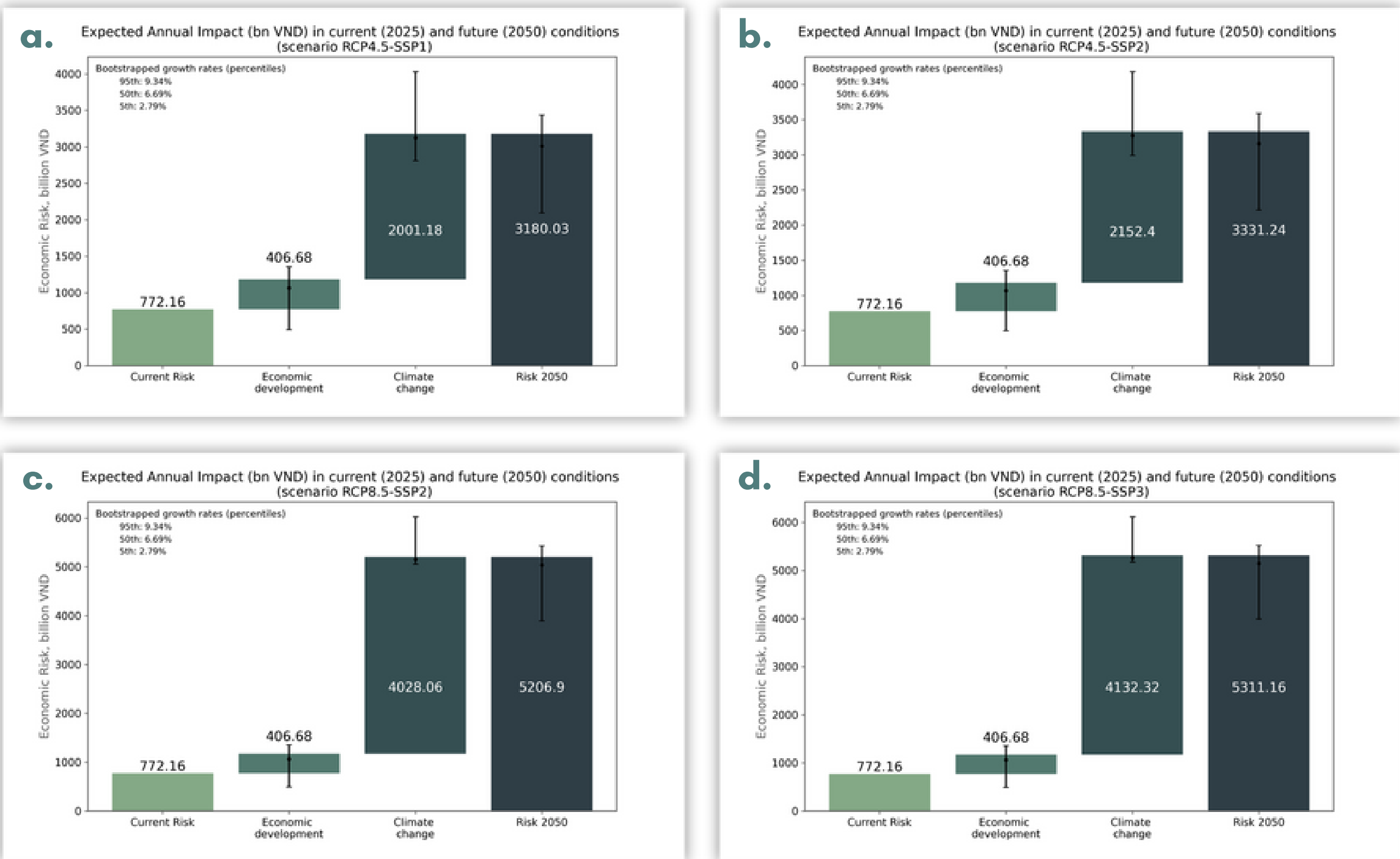


Figure 3: Comparison of Total Monetary Expected Annual Impact in 2050 across Scenarios.
a): RCP4.5-SSP1, b): RCP4.5-SSP2, c): RCP8.5-SSP2, d): RCP8.5-SSP3

With regard to people, the analysis was done purely based on the number of affected people rather than quantifying impacts in monetary terms. The current Expected Annual Impact is estimated at about 1,600 people. This figure is expected to increase to around 3,700 and 6,900, depending on the RCP-SSP scenarios. Figure 4 showcases the contributors to the expected annual impact in 2050 for each scenario. Blue indicates the current estimated population at risk, the orange bar indicates the expected increase due to population growth, the expected effects due to climate change are displayed in green, and the red bar indicates the sum of those components.

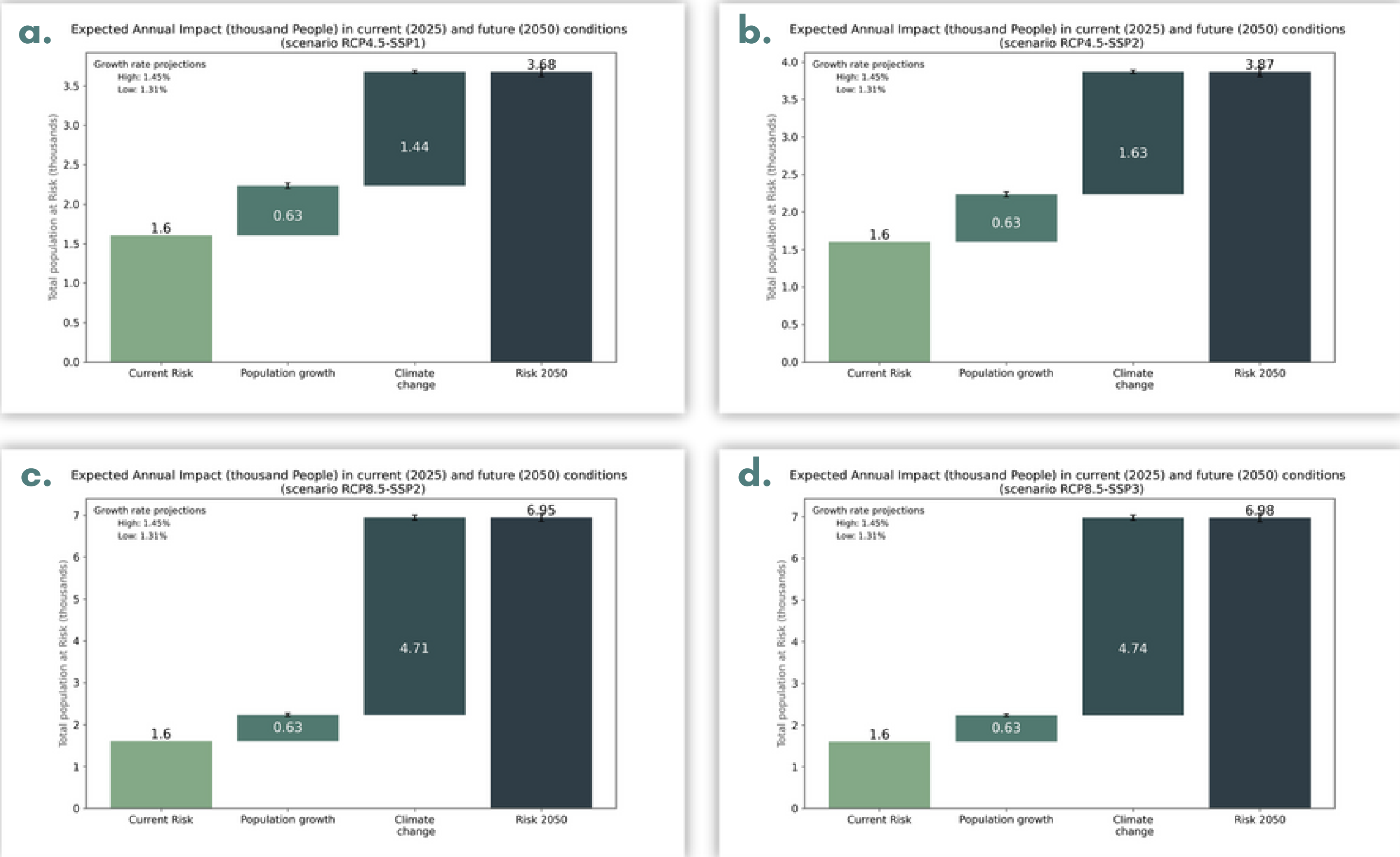


Figure 4: Comparison of Expected Annual Impact on People in 2050 across Scenarios a): RCP4.5-SSP1, b): RCP4.5-SSP2, c): RCP8.5-SSP2, d): RCP8.5-SSP3

3.2 EXPECTED BENEFITS OF ADAPTATION MEASURES

To evaluate the potential of different adaptation strategies, nine selected adaptation measures were analyzed separately for the capacity to reduce flood-related damages across assets and future scenarios. In total, if all measures are applied simultaneously in the defined setup with a total of VND 404 billion in investment needs, in the two scenarios of mild climate change (RCP4.5), the total expected risk between 2025 and 2050 can theoretically be covered fully as shown below (Figure 5) in the two left bars. The whiskers indicate again the uncertainty interval. Under the two extreme climate signal scenarios (RCP8.5), the two right bars, the risk cannot be covered with the evaluated adaptation measures, and hence leaves a protection gap. This protection gap can be addressed through different channels, e.g., through scaling up some of the measures, where possible, or through financial risk management tools (see the subchapter Risk Layering Framework below).

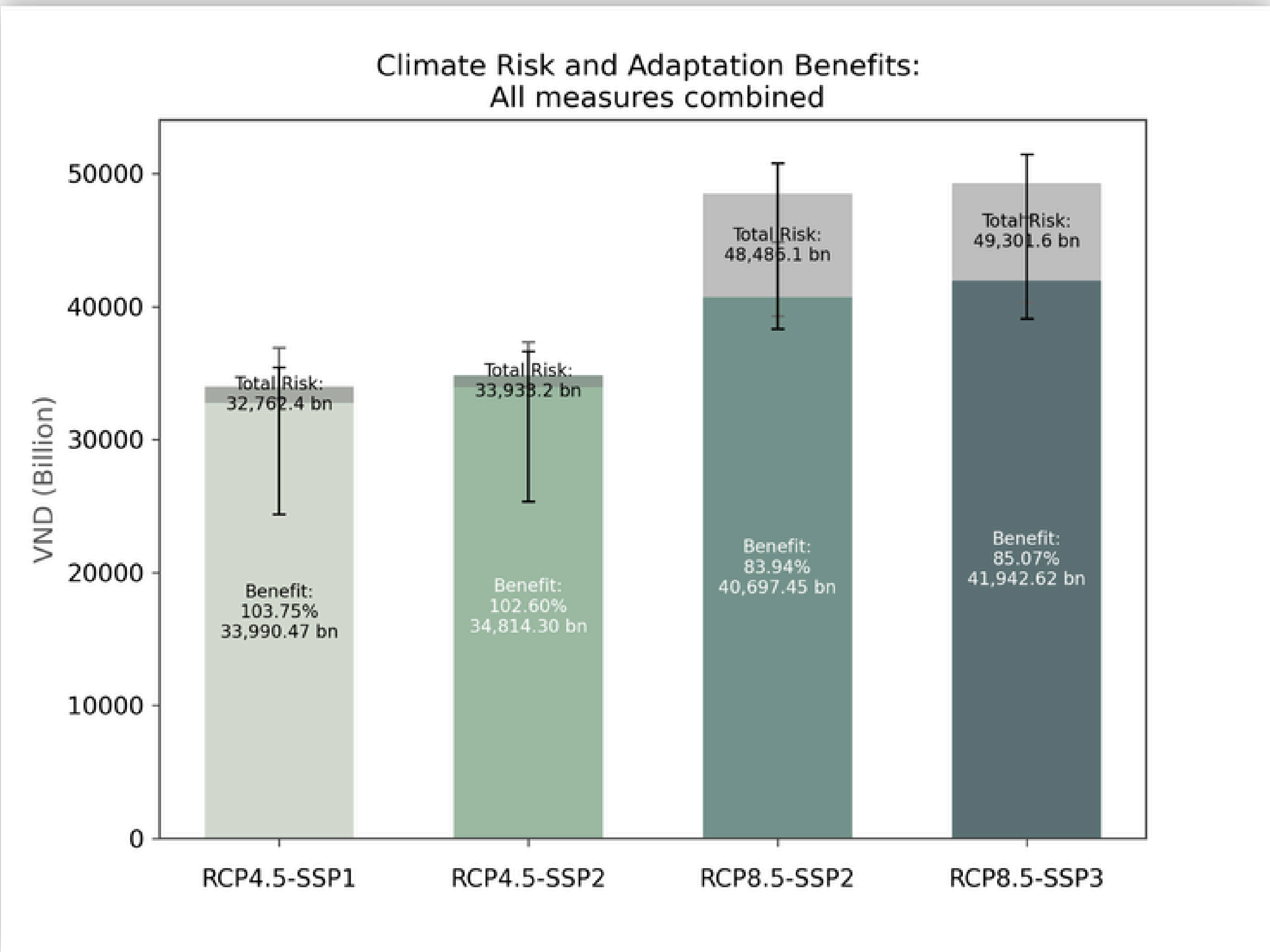


Figure 5: Total Risk 2025-2050 and Avoidance Potential of Evaluated Adaptation Measures. Whiskers indicate the uncertainty range between the 5th and 95th percentiles.

Concerning people, theoretically, the evaluated measures in the chosen exemplary calibration can fully cover the total expected number of people in the period 2025 – 2050, ranging from 45,100 (RCP4.5-SSP1) to 70,637 (RCP8.5-SSP3). Figure 6 showcases that, theoretically, the risk avoidance potential of the evaluated adaptation measures overreaches the expected number of affected people by far.

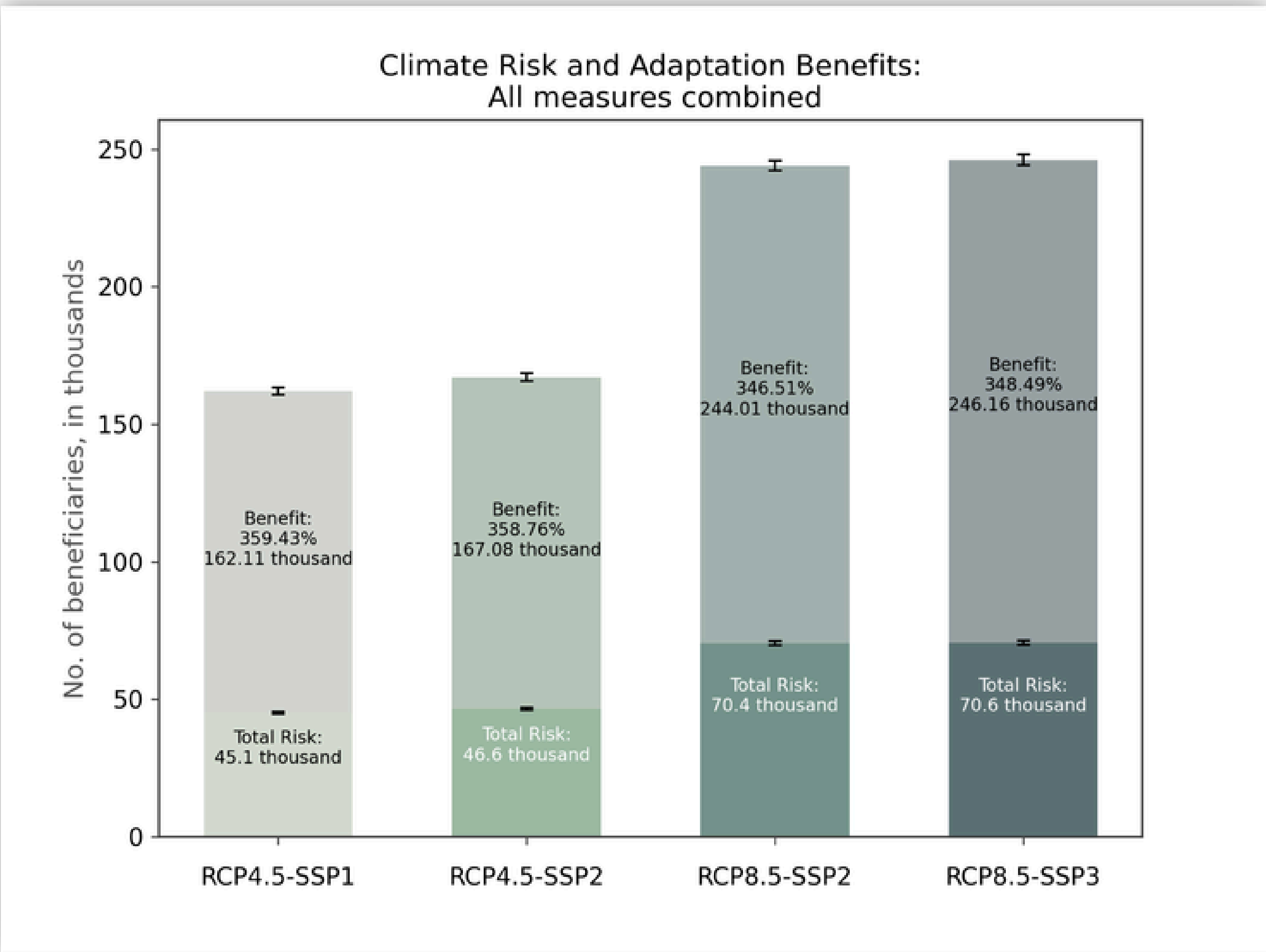


Figure 6: Total Risk 2025-2050 and Avoidance Potential of Evaluated Adaptation Measures for People
Whiskers indicate the uncertainty range between the 5th and 95th percentiles.

While the sum of the potential benefits of all measures combined is quite substantial, each measure impacts different assets differently, and thus, the averted impacts differ between asset groups. In order to limit the complexity of this report, only the top three performing measures for each asset group in the RCP4.5-SSP2 scenario will be showcased. However, similar results are available online on the FRAME platform (DLR/EOC FloodAdaptVN Consortium) for all considered assets, measures, and scenarios, and can be arranged and combined as needed.

ROAD INFRASTRUCTURE

3.2.1 Road Infrastructure

The performance of the evaluated measures is shown in Figure 7. Restoration of Natural Urban Waterbodies shows the highest benefit-cost ratio (the height of the bar) at about 50, i.e., per VND 1 million invested in the intervention, about VND 50 million in damages to road systems are estimated to be averted. The width of each bar indicates the total potential of the respective measure. The vertical and horizontal whiskers indicate the uncertainty range between the 5th and 95th percentiles of the benefit-cost ratio (height), and the potential overall impact (width). The red dashed line indicates the total expected risk accumulated over the observed period; the two purple dashed lines indicate the uncertainty range between the 5th and 95th percentiles. In the case of the Restoration of Natural Urban Waterbodies, about VND 520 billion of damage to road systems can be averted through investing in this intervention in the period 2025-2050. The panels in Figure 8 showcase the differences in impacts of the three top-performing adaptation measures in total, and the spatial distribution of different measures within the research area.

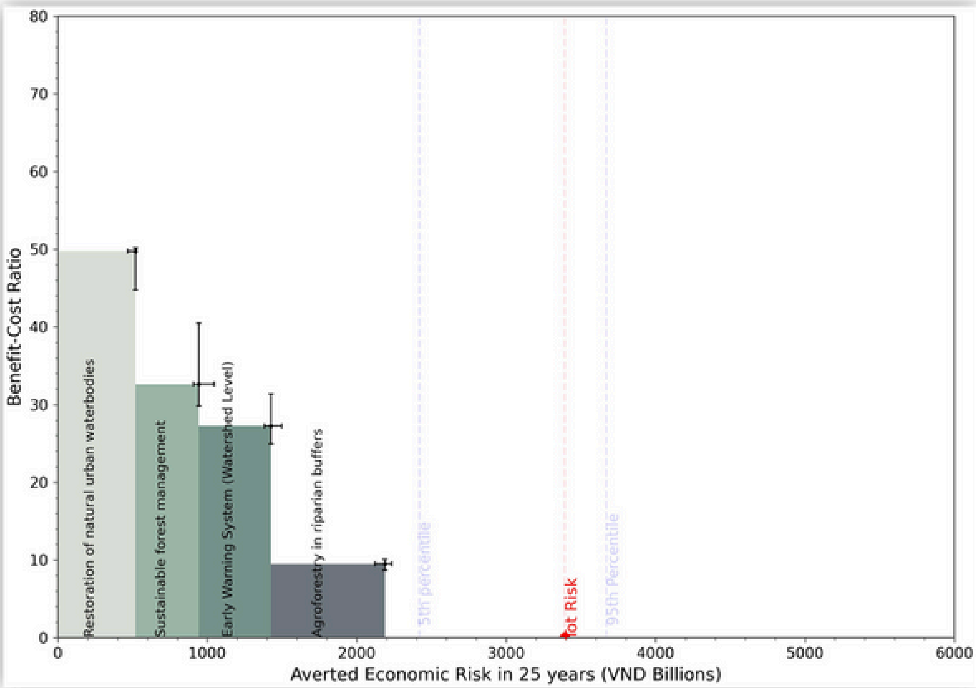
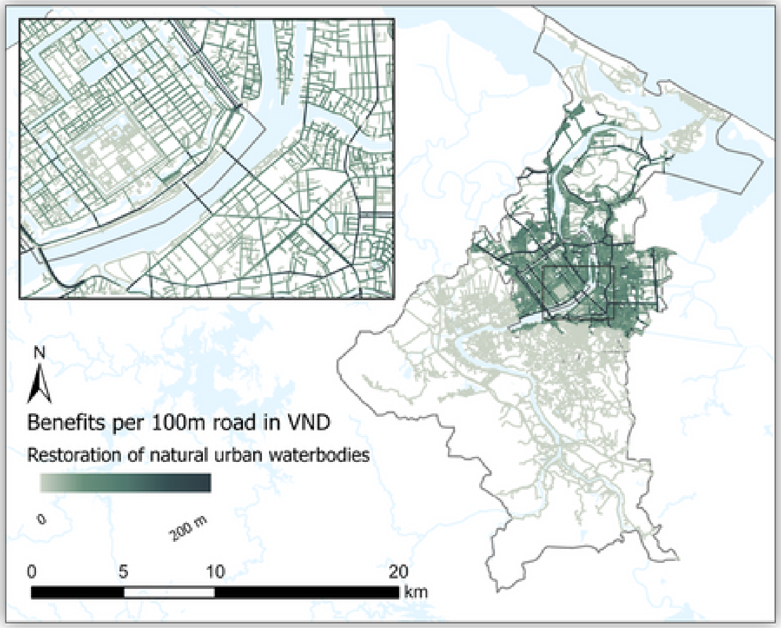
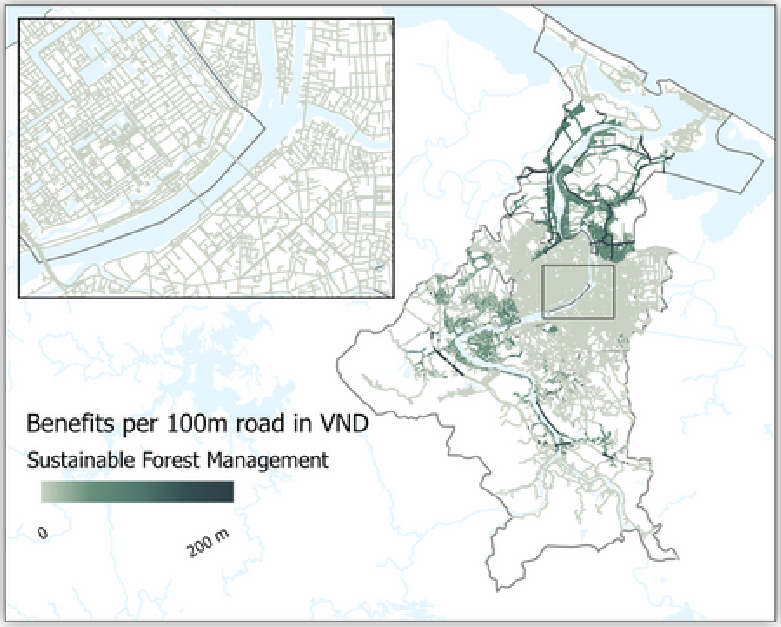


Figure 7: Benefit-Cost Analysis for Adaptation Measures Targeting Road Networks in the RCP4.5-SSP2 Scenario

ROAD INFRASTRUCTURE





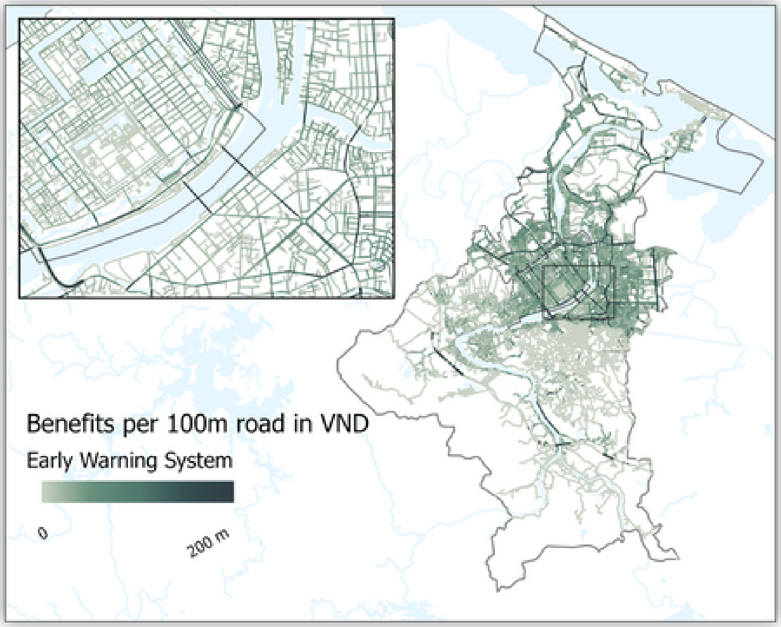


Figure 8: Benefits per 100m of Road under the Top 3 Performing Adaptation Measures

3.2.2 Railway Infrastructure

The impact on the railway infrastructure is best minimized by investing in the Restoration of Natural Urban Waterbodies, Early Warning Systems, and Agroforestry in Riparian Buffers, which all show a benefit-cost ratio above one. The fourth evaluated adaptation measure, Sustainable Forest Management, however, is not assessed as cost-beneficial. All measures combined are not expected to cover the total expected risk (Figure 9). The maps below (Figure 10) display the spatial distribution of the three adaptation measures per 100m train tracks.

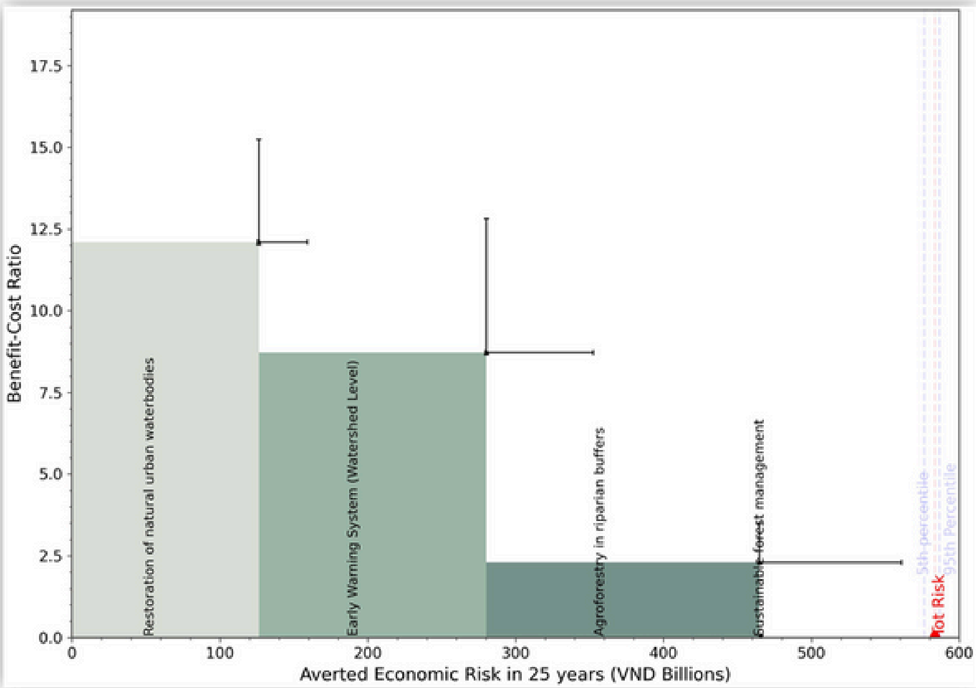


Figure 9: Benefit-Cost Analysis for Adaptation Measures Targeting Train infrastructure in the RCP4.5-SSP2 Scenario

RAILWAY INFRASTRUCTURE

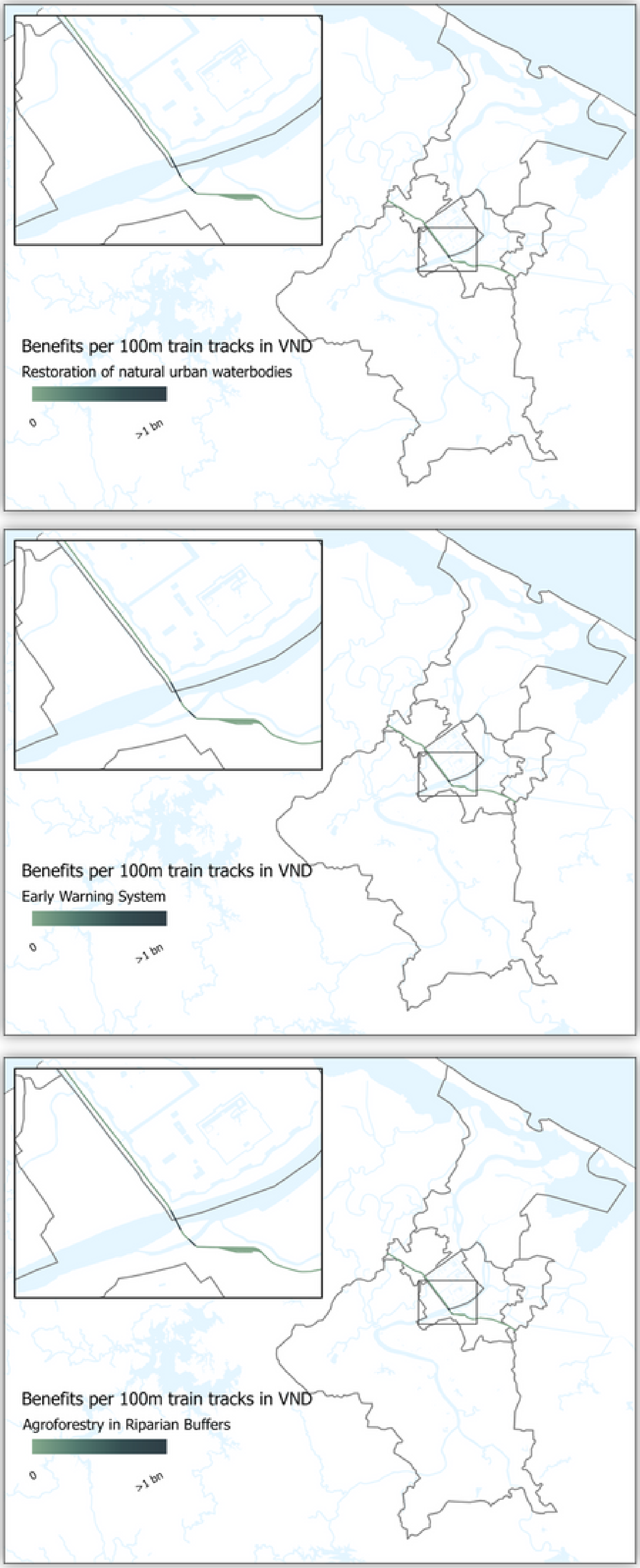


Figure 10 :Benefits per 100m Train Tracks under the Top 3 Performing Adaptation Measures

BUILDINGS

3.2.3 Buildings

In the group of buildings, the three highest performing adaptation measures in terms of benefit-cost ratio are Restoration of Natural Urban Waterbodies, Early Warning Systems and Agroforestry in Riparian Buffers (Figure 11). However, the other two adaptation measures considered show a benefit-cost ratio well above one, while the measure Housing Modifications shows by far the highest risk avoidance potential (width), which is likely because the vast majority of buildings are residential buildings, which benefit most from housing modifications. Overall, all measures combined, it is expected that the total risk faced over the 25 years assessed can be averted as the potential of all measures combined reaches beyond the red total risk marker. The panels in Figure 12 show the spatial distribution of the beneficial impact of the three best-performing adaptation measures.

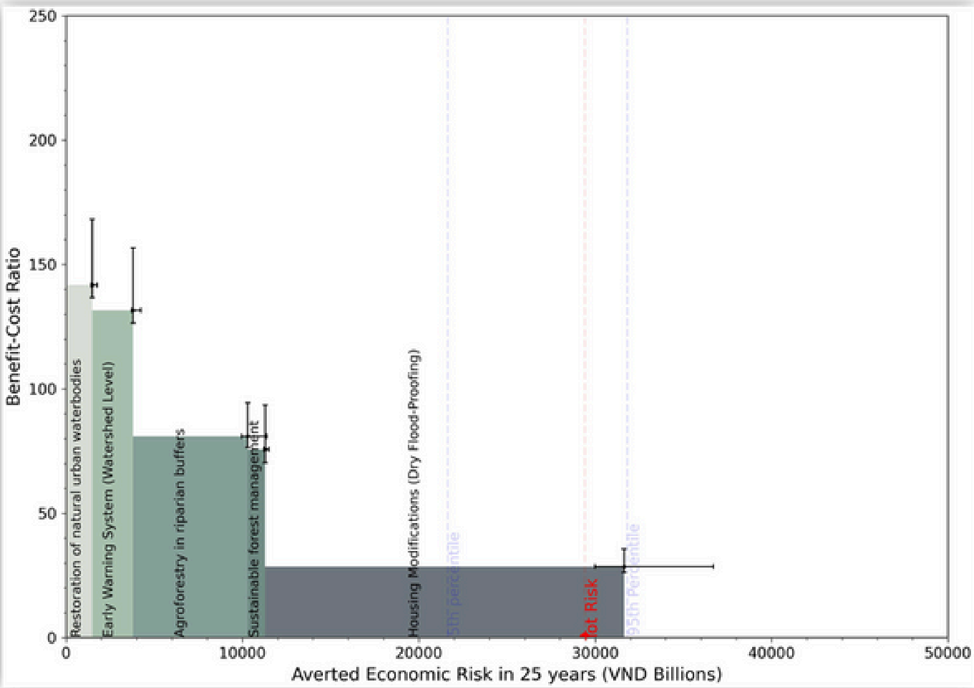


Figure 11: Benefit-Cost Analysis for Adaptation Measures Targeting Buildings in the RCP4.5-SSP2 Scenario

BUILDINGS

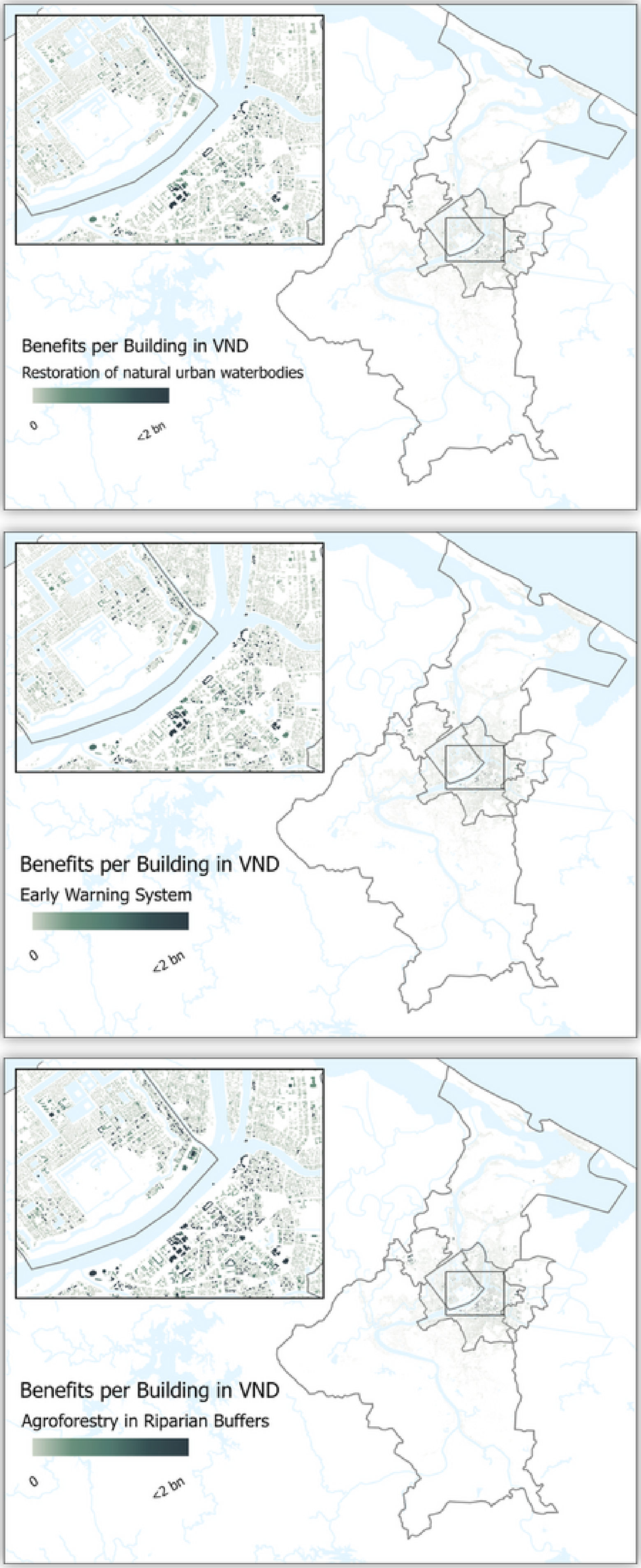


Figure 12: Benefits per Buildings under the Top 3 Performing Adaptation Measures

AGRICULTURE

3.2.4 Agriculture

For the considered crops, the top three performing adaptation measures in the RCP4.5-SSP2 scenario are Early Warning Systems, Sustainable Forest Management and Crop Insurance (Figure 13). The other measures considered show high risk avoidance potential; however, as their benefit-cost ratio lies under 1, i.e., the reduced impact is lower than the invested sum, and thus, from a purely economic point of view, it is not viable. Figure 14 showcases the difference in impact distribution of the three highest-scoring adaptation measures.

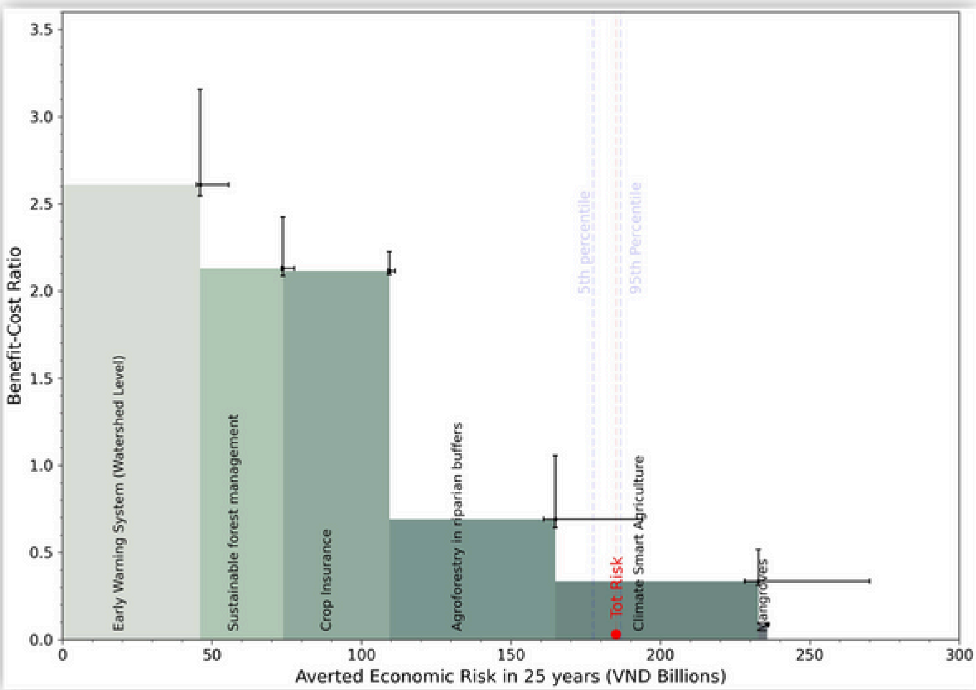


Figure 13: Benefit-Cost Analysis for Adaptation Measures targeting Crops in the RCP4.5-SSP2 Scenario

AGRICULTURE

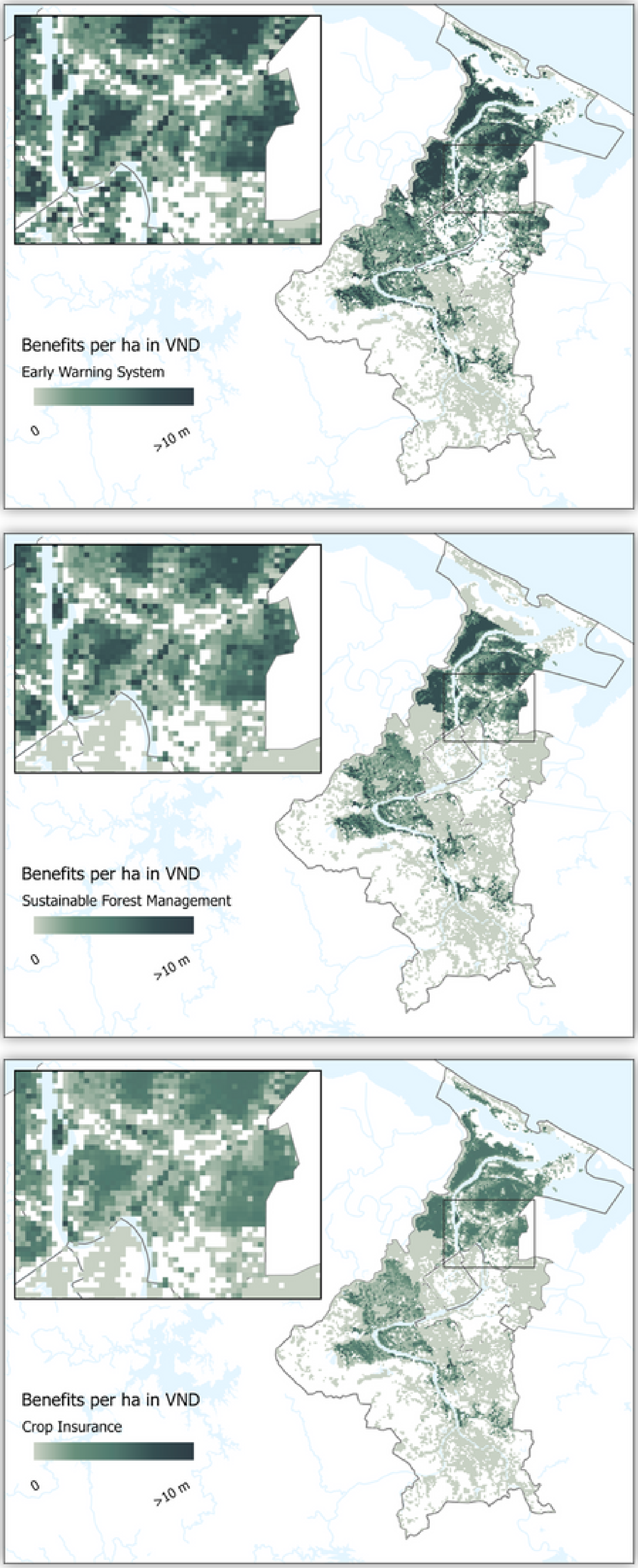


Figure 14: Benefits per ha Agricultural Land in VND for the Top 3 Performing Adaptation Measures

3.2.5 Aquaculture

The three sole evaluated adaptation measures for aquaculture assets are Early Warning Systems, Sustainable Forest Management and Agroforestry in Riparian Buffers. While Early Warning Systems and Sustainable Forest Management show a benefit-cost ratio above one, Agroforestry in Riparian Buffers does not seem cost-beneficial from a purely economic standpoint (see Figure 15). The panels in Figure 16 show the spatial distribution of where the benefits of the different adaptation measures can be expected.

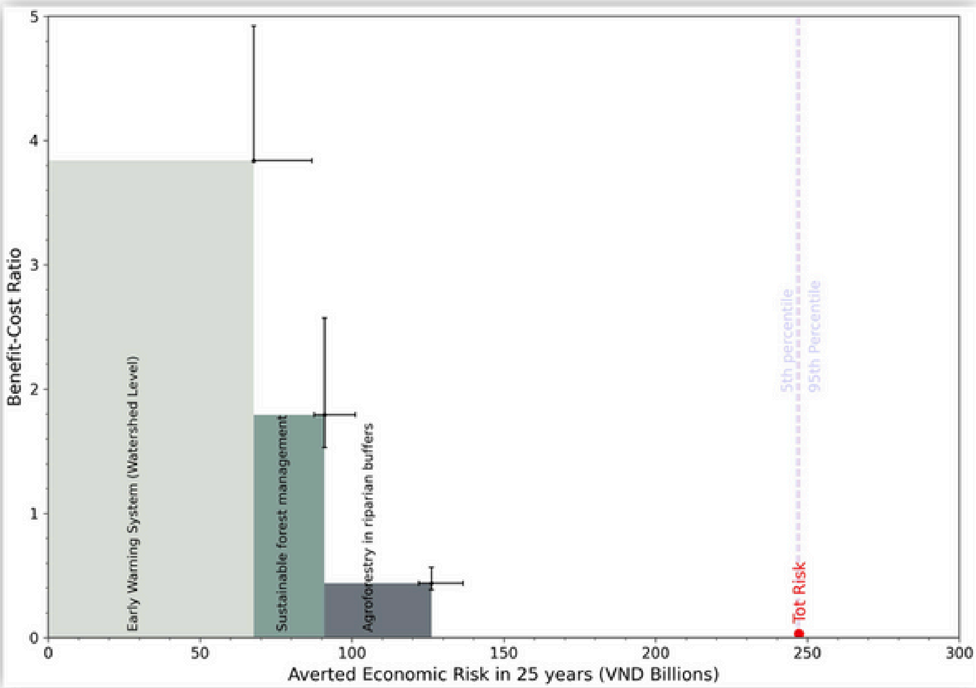


Figure 15: Benefit-Cost Analysis for Adaptation Measures targeting Aquaculture in the RCP4.5-SSP2 Scenario

AQUACULTURE

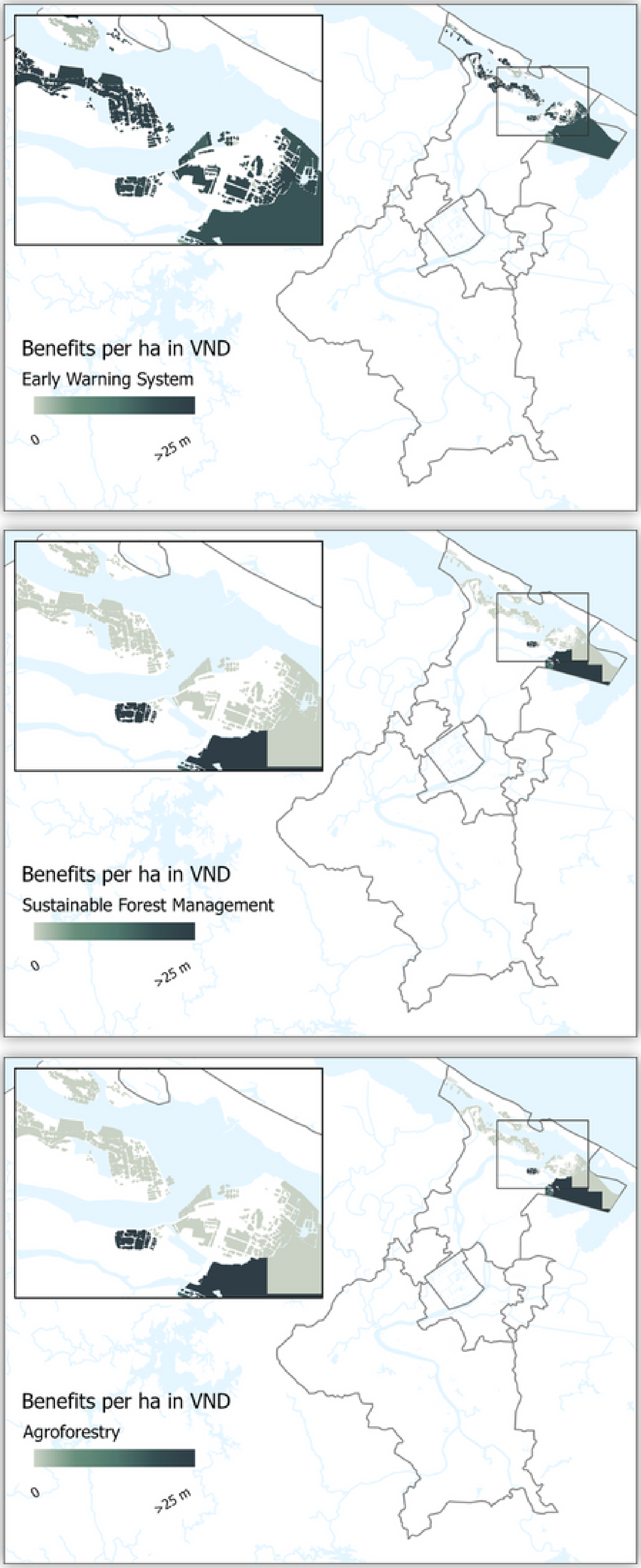


Figure 16: Benefits per ha aquaculture area in VND for the top 3 performing Adaptation Measures

PEOPLE

3.2.6 People

Concerning the last cluster, people, the best performing adaptation measures are Early Warning Systems, Restoration of Natural Urban Waterbodies, and Crop Insurance (Figure 17). However, Crop Insurance has minimal potential in terms of reaching people (indicated by the width of the bar). It is closely followed by Flood Risk Awareness Campaigns, which potentially reach a much larger group of people. Benefit-cost is in this non-monetary case expressed in “reached people per invested VND 1 million”, leaving the interpretation of what ratio is still acceptable to the respective investment decision-maker. As the total expected risk, i.e., the total expected population to be affected within the 25-year timeframe (red mark), lies within the reach of the adaptation measures, theoretically, these measures suffice to cover the population-related risks. The map panels in Figure 18 show the differences in benefit distribution of the three best-performing adaptation measures.

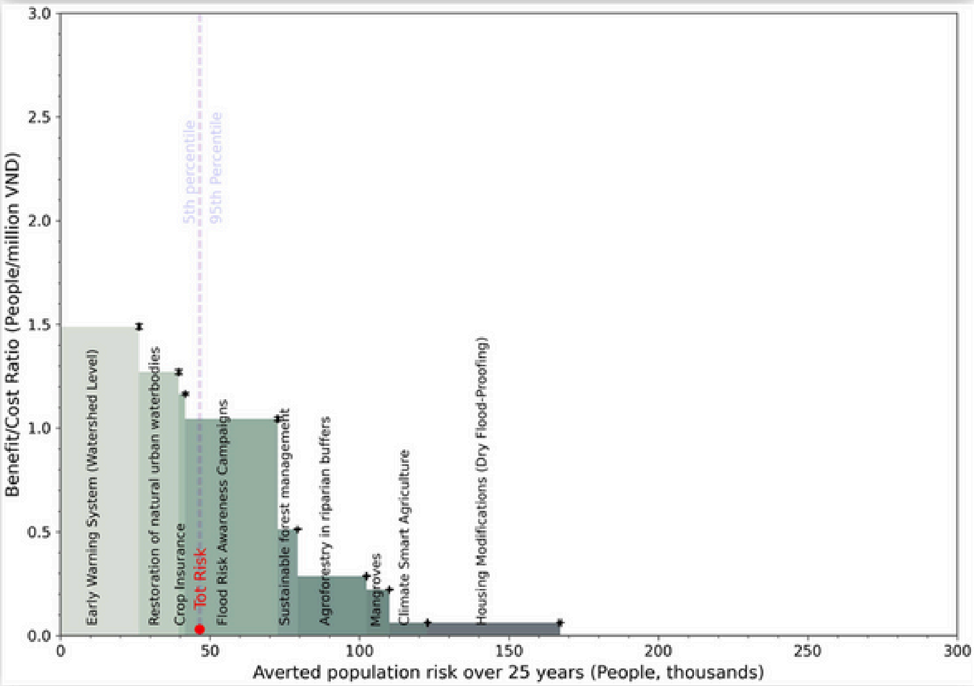


Figure 17: Benefit-Cost Analysis for Adaptation Measures targeting People in the RCP4.5-SSP2 Scenario

PEOPLE

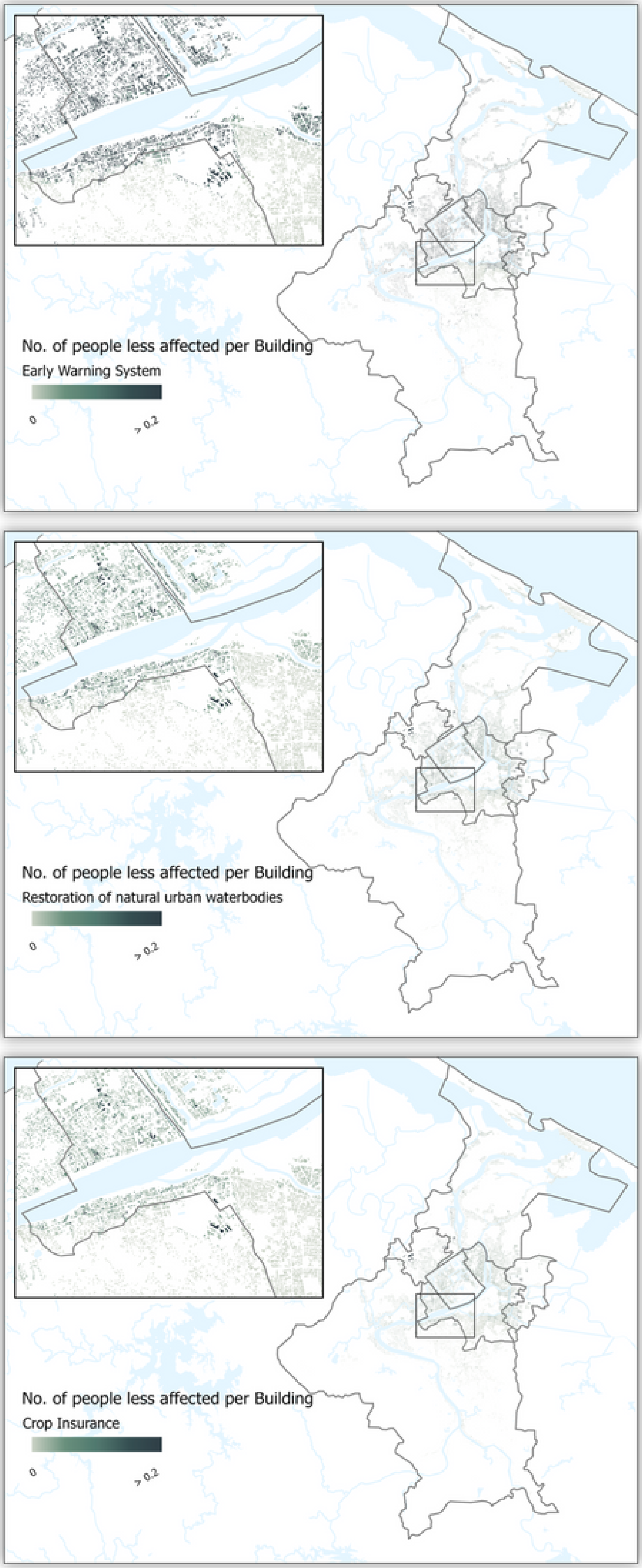


Figure 18: Benefits per Household for the Top 3 Performing Adaptation Measures

3.3 LIMITATIONS & UNCERTAINTIES

While this analysis provides valuable insights into flood risks and the benefits of adaptation strategies, several factors introduce uncertainty and should be considered when interpreting the results.

Model Assumptions and Maintenance Conditions
The analysis assumes that all selected adaptation measures are implemented immediately and operate under optimal conditions, including consistent functionality and regular maintenance, until 2050. In reality, delays in implementation, partial coverage, or insufficient maintenance could reduce the effectiveness of measures. Moreover, the model does not account for gradual deterioration, learning effects or potential increases in efficiency over time.

Spatial Resolution and Location of Adaptation Measures
CLIMADA operates on a spatially aggregated level and does not model the exact geographic placement of adaptation measures. Instead, adaptation effects are parameterized at the catchment or asset group level, without simulating site-specific configurations. This introduces uncertainty, especially for measures where location-specific design is critical for their effectiveness.

Scenario and Projection Uncertainty
All future climate and socio-economic scenarios (RCP–SSP combinations) inherently carry uncertainty regarding emission pathways, population dynamics, land-use changes and governance developments. In addition, the climate modelling itself represents a potential source of error that propagates into flood modelling. These assumptions directly influence the hazard, exposure and risk outputs, and reflect plausible but not definitive future conditions.

Data Availability and Calibration Challenges
The reliability of the risk estimates depends on the quality and completeness of input data, including exposure values, vulnerability curves and hazard footprints.

Particularly, the economic valuation of assets—especially infrastructure such as roads—relies on cost approximations and literature-derived estimates where local data were unavailable. Vulnerability (damage) functions were calibrated using available local damage reports and supplemented with generic functions, e.g., from JRC (Moel et al. 2016) and the Can Tho study (Behre et al. 2021). However, limited historical records and damage data remain a constraint, introducing uncertainty into the calibration.

Exclusion of Co-benefits and Non-Monetary Values
The analysis focuses on direct flood damage reduction expressed in monetary terms. Other important co-benefits of adaptation measures—such as biodiversity protection, carbon sequestration or social resilience—were not quantified within the CLIMADA framework. These aspects are discussed in more detail in the complementary report on Opportunities for improved flood risk management and adaptation in Hue, Central Viet Nam (Ortiz Vargas et al. 2025).

Static Exposure and Vulnerability Assumptions
The analysis assumes static exposure and vulnerability conditions over time, without factoring in potential changes in urban development, asset distribution or building quality. Given the expected urban growth and socio-economic transformations in Hue, this assumption likely leads to an underestimation of both future risks and the potential benefits of adaptation measures.

Summary
These limitations highlight the need for a careful interpretation of the results. The presented risk estimates and adaptation benefits should be understood as indicative and comparative rather than precise forecasts. Continuous data improvements, local validation and the inclusion of non-economic and co-benefit dimensions are recommended for future refinement of the analysis.

4.

ADDRESSING THE ADAPTATION GAP THROUGH RISK LAYERING AND CLIMATE AND DISASTER RISK FINANCE AND INSURANCE (CDRFI)

While the implementation of top adaptation measures—such as early warning systems, agroforestry in riparian buffers, and elevated roads—significantly reduces flood-related damages, a residual risk remains. This "adaptation gap" encompasses the portion of risk that cannot be mitigated through the selected adaptation strategies, either due to technical limitations or cost constraints.

To effectively manage this residual risk, a comprehensive risk management approach is necessary. This involves the integration of various financial instruments tailored to the frequency and severity of potential flood events, a concept known as risk layering.

4.1 RISK LAYERING FRAMEWORK

To manage the residual adaptation gap effectively, financial instruments can be employed in a sequenced and combined manner according to return periods and impacts of different flood events. The following risk layering framework (shown in figure 19) briefly introduces the most appropriate financing mechanisms to high-frequency, moderate-frequency and low-frequency flood scenarios.

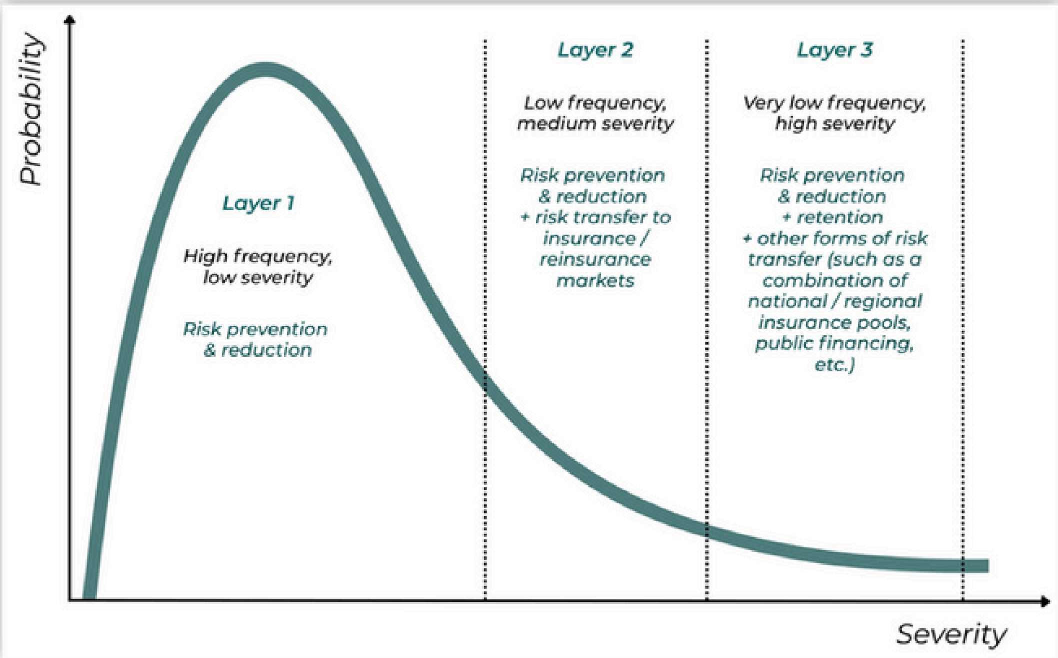


Figure 19: Risk Layering Framework

- High-Frequency, Low-Severity Events: These are frequent but less severe flood events. Managing these risks typically involves risk retention strategies, such as establishing contingency funds, budget reserves or securing contingent credit lines. These instruments provide immediate liquidity to address minor damages without relying on external assistance.

- Moderate-Frequency, Moderate-Severity Events: Events in this category may be addressed through contingent credit arrangements or reserve funds that can be rapidly mobilised to provide necessary funding for response and recovery efforts.

- Low-Frequency, High-Severity Events: These rare but catastrophic events often require risk transfer mechanisms. Instruments like parametric insurance, catastrophe bonds and participation in sovereign risk pools enable the transfer of substantial financial risks to third parties, ensuring rapid access to funds for recovery and reconstruction.

This layered approach ensures that each type of risk is managed using the most appropriate and cost-effective financial instrument, enhancing the overall resilience of the Huong River catchment area.

4.2 INTEGRATING CLIMATE AND DISASTER RISK FINANCE AND INSURANCE (CDRFI)

While the risk layering framework outlines which types of instruments align with specific hazard profiles, the Climate and Disaster Risk Finance and Insurance (CDRFI) concept delves deeper into operationalizing these instruments to close the adaptation gap. Drawing on the Strategic Evidence Roadmap (InsuResilience Global Partnership and Munich Climate Insurance Initiative 2021) and the UNU-EHS/MCII primers (Denno Cissé 2021; United Nations University Institute for Environment and Human Security and Munich Climate Insurance Initiative n.d.) the following elements enrich and extend the basic risk layering approach:

- Governance & Institutional Arrangements: Establish clear mandates and coordination platforms across finance, disaster management and water authorities. Embedding CDRFI into municipal and provincial budgeting cycles ensures that contingency funds and premium payments are sustained over time.
- Market Development & Capacity Building: Support the development of local insurance markets and parametric product providers through public–private partnerships, technical assistance and regulatory frameworks (e.g., standardized index definitions and payout protocols).
- Subsidies and Blended Finance: To ensure affordability for vulnerable households and small businesses, targeted premium subsidies or blended finance structures can be used, combining grant contributions with market-rate capital to reduce the cost burden for end-users.
- Linking Mitigation with Financing: Insurers and financiers can offer premium discounts or enhanced coverage when clients implement verified risk-reduction measures (e.g., riparian buffer zones, improved drainage, floodproofing), creating incentives to invest in adaptation.
- Data, Transparency & Monitoring: Robust data on hazard, exposure and loss experience feeds parametric trigger definitions and improves pricing accuracy. Publicly accessible dashboards tracking fund balances, payouts and risk levels foster accountability and trust.

By embedding these operational elements within the layered structure, CDRFI evolves from a menu of instruments into an integrated, sustainable financing architecture—one that supports not only post-flood recovery but also proactive risk reduction and long-term resilience building.

Thus, implementing a risk-layered CDRFI strategy aligns with global best practices and frameworks. It encompasses a suite of financial tools designed to provide timely and reliable funding in the aftermath of climate-induced disasters. By integrating CDRFI into the broader risk management strategy, stakeholders can ensure that financial resources are available to address the adaptation gap effectively.

5.

CONCLUSIONS

In this report, a comprehensive quantitative analysis of flood risk and adaptation strategies in the Huong River catchment with a special focus on Hue City is provided. Utilizing the CLIMADA modelling framework, we assessed the potential impacts of various adaptation measures under different climate and socio-economic scenarios. The focus was on quantifying the economic benefits of these measures through a benefit-cost analysis.

While the benefit-cost analysis offers valuable insights into the economic efficiency of adaptation options, it is important to recognize that other factors—such as social equity, environmental sustainability, and institutional feasibility—also play critical roles in decision-making. These aspects are explored in greater depth in the accompanying Flood Risk Report (Sett et al. 2025) and Opportunities for improved flood risk management and adaptation in Hue, Central Viet Nam: Addressing current and future flood risks report (Ortiz Vargas et al. 2025).

Based on the aggregated analysis across all assets and measures, the top-performing measures, in terms of impact avoidance potential in VND, with varying benefit-cost ratios across the different asset groups, are:

- **Housing Modifications:** About VND 20,362 billion worth of damage could be avoided by implementing dry-flood proofing housing modifications between 2025 and 2050
- **Agroforestry in Riparian Buffers:** An estimated VND 1,268 billion worth of damage can be avoided by initiating and maintaining agroforestry in the riparian buffer zones over the next 25 years
- **Restoration of Natural Urban Waterbodies:** About VND 539 billion worth of impact could be avoided by investing in the restoration of natural urban waterbodies between 2025 and 2050

Concerning benefit-cost ratios, the most prominently featured measures under the respective asset groups' top three are:

1. **Early Warning Systems:** For each observed asset group, Early Warning Systems are among the top three adaptation measures
2. **Restoration of Natural Urban Waterbodies:** For five of the seven asset groups, restoration of natural urban waterbodies is ranked among the top three adaptation measures
3. **Agroforestry in Riparian Buffers:** While this adaptation measure never achieved the top ranking spot in any asset group, implementing agroforestry in riparian buffers was ranked in the top three adaptation measures for four of the seven asset groups.

Overall, the evaluated adaptation measures show a high potential to avoid all, or a large portion of, the expected future impacts. Especially in the two considered RCP4.5 scenarios, the expected benefits of the measures, if all are implemented, surpass the expected future monetary impacts. In the two scenarios considering a more extreme climate signal, RCP8.5, the measures are still able to avoid more than 80% of the expected impact in either scenario. In the case of people, the same adaptation measures are expected to cover the future risk completely in either scenario.

6.

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