Economics of Climate Adaptation

Report 03

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Vulnerability Report

UNITED NATIONS UNIVERSITY
UNU-EHS

San Pedro Sula - Honduras
Urban Flood Risk

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List of Acronyms

Annual Expected Damage (AED)

Comisión Permanente de Contingencias Honduras (COPECO)

Cross-Section (XS)

Departamento de Investigación y Estadística Municipal (DIEM)

Digital Elevation Model (DEM)

Disaster Risk Management (DRM)

Economics of Climate Adaptation (ECA)

Ecosystem Services Valuation Database (ESVD)

Fondo Hondureño de Inversión Social (FHIS)

German Development Bank (KfW)

German Ministry for Economic Cooperation and Development (BMZ)

Global climate model (GCM)

Hydrologic Engineering Center's - Hydrologic Modeling System (HEC-HMS)

Hydrologic Engineering Center's - River Analysis System (HEC-RAS)

Instituto Nacional de Estadística (INE)

Integrated Risk Management in Honduras (PEGIRH)

Intergovernmental Panel on Climate Change (IPCC)

InsuResilience Solutions Fund (ISF)

Law of the National Risk Management System (SINAGER)

Light Detecting And Ranging (LIDAR)

Mean damage degree (MDD)

Necesidades Básicas Insatisfechas (NBI)

Plan Maestro de Desarrollo Municipal (PMDM)

Representative Concentration Pathway (RCP)

Rossby Centre Regional Climate Model (RCA4)

San Pedro Sula (SPS)

The Economics of Ecosystems and Biodiversity (TEEB)

United Nations Economic Commission for Latin America and the Caribbean (UNECLAC)

United Nations University - Institute for Environment and Human Security (UNU-EHS)

1 INTRODUCTION

Storms, floods, droughts and other extreme weather events can threaten urban and rural areas, from small regions to entire nations. Along with growing populations and economies, losses from natural hazards are rising in the world's most exposed regions as our climate continues to change. The Economics of Climate Adaptation (ECA) is a decision-making support framework that integrates climate vulnerability and risk assessments with economic and sustainability impact studies to determine the portfolio of optimal adaptation measures for diverse climate risks.

The United Nations University - Institute for Environment and Human Security (UNU-EHS) in cooperation with and funded by the InsuResilience Solutions Fund (ISF), is implementing the Economics of Climate Adaptation (ECA) framework in the Municipality of San Pedro Sula (SPS) in Honduras to identify the most cost-effective measures to address the negative impacts of floods. The ISF is funded by the German Development Bank (KfW) and commissioned by the German Ministry for Economic Cooperation and Development (BMZ). Currently, the Economics of Climate Adaptation (ECA) methodology is being implemented in three different countries (Vietnam, Honduras and Ethiopia).

After concluding the inception phase and compiling and validating data with key stakeholders for running CLIMADA during the base data phase, this report presents the final recommendations for adaptation measures to flood events in the Municipality of San Pedro Sula. A major source of information for the study is the Plan Maestro de Desarrollo Municipal (PMDM), which the Municipality carried out through extensive research and data collection. An important part of the socio-economic characterization and costing of the ECA study is based on the PMDM, in addition to a household survey that the Municipality run on historical damages of floods in the vulnerable areas of San Pedro Sula. In the following chapters the reader is provided with an overview of the inputs for CLIMADA in terms of hazards, assets, damage functions and adaptation measures, and further discussions are made to clarify the assumptions and uncertainties involved in the process. This document closes with conclusions and recommendations for the administration and an additional chapter on the last phase of the ECA study which is a pre-feasibility analysis of the measures suggested.

During the last few months, a set of calls and workshops were organized for key representatives of the Municipality to provide input and request clarification on the subjects of the flood model used in the study, asset valuation methods and the modelled adaptation measures. The flood model used for the ECA study was an upgrade from the model developed by COPECO in 2016 for their "Risk analysis at the municipal and local level[1]", but focused on the floodplains located within the districts agreed with the Municipality during the Inception Workshop, see Chapter 2.

Within the asset valuation workshop, the valuation method was discussed and validated for each of the asset groups identified during the Inception phase. The recommendations from the experts were incorporated and details of the results can be found in Chapter 3. Similarly, the adaptation measures' workshop leveraged the knowledge of the key experts invited, to coordinate a prioritization method that based on a given criteria, scored the adaptation measures to better reflect the local conditions. The outcomes of the workshop and the overall process and results are summarized in Chapter 5.

A total of 14 flood adaptation measures were identified and validated by the Municipality to be run in CLIMADA, including: technological and engineering solutions, ecosystem-based (nature-based) approaches, maintenance/operational measures, instruments and tools that improve baseline hydro-meteorological data, and risk transfer/insurance solutions. All details related to the measures can be found in ANNEX 5 and ANNEX 6.

Chapter 4, presents the damage functions of each asset group, which reflect the sensitivity of them to different intensities of flood. Given the scarcity of data of historical damages, different sources were used to verify and validate the assumptions made, including local surveys, international publications and calibrations through CLIMADA.

The final results coming from CLIMADA, as well as a comprehensive discussion on their expected costs and benefits, and the related uncertainties, can be found in Chapter 6. Chapter 7 compiles the conclusions and recommendations of the report, including some additional suggestions that were not modelled, but that showed a significant potential for the Municipality to improve its ability to prepare and respond for future flood events.

[1] COPECO: Comisión permanente de contingencias. (2016a). Informe V- Hidrología, Producto 1. Análisis de Riesgo a nivel municipal y local, Estimación de Avenidas – Sistemas de cuencas del Municipio de San Pedro Sula Departamento de Cortés. San Pedro Sula.

2 FLOOD MODELLING

2.1 Background and COPECO's Baseline Model

This section presents the setup of a new hydrological HEC-HMS models for Río Blanco and Río Bermejo and an update of the existing HEC-RAS flood model provided by COPECO for the municipality of San Pedro Sula. Using new datasets and a two-dimensional approach, discharge values and flood areas are depicted for the three major rivers Río Chamelecón, Río Chotepe and Río Blanco, including their larger tributaries. The new hydrological-Hydraulic simulation offer two main improvements i) a hydrologic modelling based on three return periods (25, 50 and 100 years) for the present state and the future scenarios agreed with the Municipality during the base data workshop (RCP 4.5 and RCP 8.5) and ii) spatial extension and improvement of the existing hydraulic 1D model to a 2D model approach.

2.1.1 The COPECO Model

In the last years, several studies explored flood hazard in San Pedro Sula region. COPECO conducted a detailed investigation in 2016[2] with the objective to provide a tool to support the municipality of San Pedro Sula in the creation of land management plans. Thereby the purpose was to minimize both, the economic impact of flood events the infrastructure and the live of the inhabitants. Evaluating hydro-meteorological information, flood extends for the return periods 25, 50 and 100 years were estimated, using a hydraulic 1D model (HEC-RAS). With the estimated flow, the topography of the site and the channel characteristics, flood levels were computed. The COPECO-project focused on the areas in proximity to the rivers Río Blanco, Río Bermejo (with Río Chotepe and Canal Sauce as tributaries) and Río Chamelecón, as well as Cofradía.

An additional study was conducted in 2019. It investigated further flooding in the catchment of Río Chamelecón in the Sula Valley. A region, which in the past, was exposed to the hurricane events Fifi and Mitch. These events caused heavy damages, especially in the city of La Lima. In order to update warning thresholds for the Chamelecón River, the hydraulic transit of the flood flows was considered, using HEC-RAS as a hydraulic model. The consideration of the channels Filopo and Maya played a crucial role, since their hydraulic capacity influence flooding significantly.

These studies and their findings were carefully analysed and the provided data was quality checked in order to use the existing models and results for further development of the hydrologic and hydraulic modelling approach. ANNEX 1 presents a detail account of the data used in these studies.

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[2] COPECO: Comisión permanente de contingencias. (2016a). Informe V- Hidrología, Producto 1. Análisis de Riesgo a nivel municipal y local, Estimación de Avenidas – Sistemas de cuencas del Municipio de San Pedro Sula Departamento de Cortés. San Pedro Sula.

2.1.2 Main Improvements

The scope of the flood modelling exercise presented below is therefore to improve the existing flood model for the region of San Pedro Sula. The research conducted by COPECO[3] and in 2019[4] constitutes a solid fundament. The following improvements were carried out:

1) Physical improvements of the modelling cascade:
   a. Conversion from a 1D-hydraulic model-setup to a 2D model approach with HEC-RAS for the Rivers Río Blanco, Río Bermejo as well as Río Chamelecón.
   b. Hydrological modelling of the upper catchments as well as inclusion of the canal sauce
   c. Creation of dynamic flood hydrographs by using unsteady flow hydrographs as boundary condition for hydraulic modelling (instead of assuming a steady flow rate)
2) Terrain representation
   a. DEM improvement (5m and 1m resolution) with integrating of cross section data to remove artefacts, obstacles and unnatural elevations in the river bed;
   b. Inclusion of building structures of formal and informal settlements in the DEM
3) Inclusion of climate scenarios
   a. Hydrological modelling of present and future boundary conditions for two scenarios as agreed with the Municipality during the base data workshop (future high RCP 8.5 and future low 4.5)
   b. Simulation of flood footprints for 25-, 50- and 100-year return periods for three scenarios (present, future high, future low)

2.2 Input data and methodology

2.2.1 Data

As in most regions with ungauged catchment, many assumptions are necessary to represent physical processes. However, in this ECA study, we strived to collect the best available data. All input data were carefully quality checked and discarded or improved if necessary. The following sections describe the main inputs. Additional details are available in ANNEX 2.

2.2.1.1 Digital Elevation Model

A Digital Elevation Model (DEM) is one of the most important component in a flood model. The quality of the flood model depends highly on the quality of the DEM. Especially spatial and elevation resolution is important. In the case of SPS, the analysis was carried out with different resolutions based on the raw LIDAR DEM (1m)[5] to rebuild the existing river network. For the flow accumulation spatial resolutions of 5, 10, 25, 50 and 100m were utilized. Depending on slopes and other characteristics, several sub-catchments were allocated several resolution in order to construct a so-called hydrological DEM. A hydrological DEM allows to define rivers, flow accumulation and catchments with high accuracy.

Based on the hydrological DEM, the subdivision of catchments was refined, taking into account changes in altitude and differences in the amount of settlements. For the flood model, the highest

[3] COPECO: Comisión permanente de contingencias. (2016b). Informe Geomorfológico. San Pedro Sula: Municipio de San Pedro Sula Departamento de Cortés.

[4] Abrego Suárez, C. R. (2019). Actualización preliminar de los umbrales de alerta por inundación de Río Chamelecón en ciudad La Lima, Cortés, para el período de observaciones 2010-2018. Tegucigalpa, Honduras.: Master Thesis.

[5] LIDAR (1m) from 2017 provided by COPECO. DTM (5m) provided by COPECO.

possible resolution (1m in the low lands and 5m in the rest of the study area) was used. The highest resolution, ensures flood water flow to be reproduced accurately.

2.2.1.2 Precipitation

In addition to the DEM, precipitation data is one of the most critical input to simulate the water cycle. Unfortunately, the availability of precipitation data with high temporal resolutions (sub-daily) is limited for the Sulla Valley region. Several data sources were carefully evaluated, and the FHIS (2002)[6] dataset provides the best information in terms of temporal resolution. Precipitation stations were quality-checked and their records used to determine precipitation depth for short durations storms.

The applied storm characteristics were based on the following assumptions: The storm will be applied equally to the whole sub-catchment with the same duration and the same precipitation depth over time.

2.2.1.3 Future Scenarios

For the design of the future scenarios, future precipitation changes were examined using the regional climate model RCA4 and the scenarios RCP4.5 and RCP8.5. The regional climate Model RCA4 provides daily precipitation with a spatial resolution of about 0.44° (approximately 50 km). The dataset was separated into a past and a future time period (past: 1950 – 2005; future 2006 – 2100) for a statistical analysis done in cooperation with the UNU to obtain statistical precipitation depths for the return periods 25, 50 and 100 years.

2.2.1.4 Multipurpose Dam

The El Tablón dam, currently in planning, was considered as an additional future scenario. Information about the El Tablón dam is limited but several planned discharge values were made available by the Municipality. Information on storage-discharge, elevation-discharge or elevation-storage was not available. Several assumption, detailed in ANNEX 2, were made in order to introduce the dam. They include:

1) Shifting of Dam location upstream inflow the corresponding watershed
2) Calculating the contributing areas of the dam
3) Locating the discharge peak and adjusting for the reservoir's effect
4) Applying the modified hydrograph to the hydrological model (downstream)

2.2.2 Methodology

2.2.2.1 Hydrological Modelling

Concerning the hydrological modelling, a new model was set up for the rivers Río Blanco and Río Bermejo using the software HEC-HMS, developed by the U.S. Army Engineer Hydrologic Engineering Centre (HEC). For Río Chamelecón an existing HEC-HMS model was enhanced. This modelling approach is especially suitable for ungauged catchments, where no runoff data is available for statistical analysis. With the rainfall-runoff approach it is possible to perform hydrological analyses and to study the consequences of intended man-made changes within the catchment (e.g. landuse change, reservoirs).

Applying a hydrological model for event-based analysis requires the description and parametrization of relevant components of the hydrological cycle. Some components, such as evapotranspiration, may

[6] Fondo Hondureno de Inversion Social Dirrection de Medio Ambiente (2002) manual de referencias hidrologicas de honduras (2002)

be neglected, due to the short timescale of most storm events. The description of the remaining components mainly covers total precipitation, the infiltration loss, the resulting direct surface runoff, the concentration of surface water into the next river (overland flow) as well as the routing of river-water within the channel.

Driven by data availability and data resolution, the hydrological model was set up as a semi-distributed model, dividing the whole basin into a number of smaller sub-watersheds with relatively homogeneous physical characteristics. These physical characteristics were determined on the base of available data (e.g. land use, soil, elevation range/slope) and a GIS-based analysis to derive the parameterization of the physically-based description of the hydrological cycle components. Subsequently, the catchment of Río Bermejo (228 km²) was subdivided into 47 sub-catchments, of which each was parameterized. For Río Blanco (108 km²) a subdivision into 30 sub-catchments took place. The parameterisation of the catchment of Río Chamelecón was provided by the prior existing model and adopted for a short storm duration with less than 24 h.

2.2.2.2 Flood Model

The base for the set-up of the 2D flood model formed the 1D models created by COPECO in 2016 (COPECO 2016a). These models included a DEM, which was used for the 2D hydrodynamic, unsteady modelling process. Before creating the model terrain in HEC-RAS the DEM was re-analysed. Especially the profiles of the rivers were corrected. Additional details in ANNEX 2.

As measured cross-section (XS) profiles were not available, except for a partial section of canal sauce of approximately 2 km, it was decided the use the XS profiles from the 1D COPECO model, which had been extracted from the DEM, to create a plausible, smooth river profile (See ANNEX 2, p29 for additional details). Before doing so, the centrelines of the rivers were readjusted. This was done manually based on satellite data and the available DEM. Subsequently, the bank-stations of the remaining XS stations were adapted accordingly. Having created a consistent channel (the width was also selected based on satellite imagery), it was possible to burn these channels into the DEM. This process was done iteratively for each river, until a plausible channel profile was obtained.

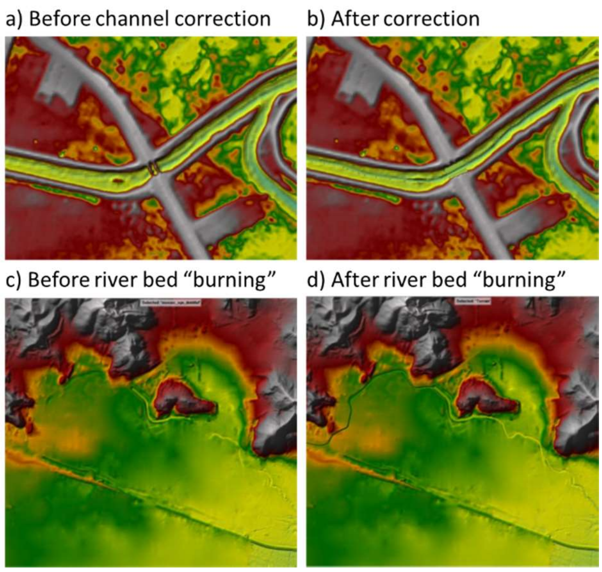

Figure 1 Example of DEM enhancement (before a and c and after d)

The major rivers, which have led to flooding events in the past, posing a risk to San Pedro Sula and its outskirts, are the rivers Río Blanco, Río Bermejo, Río Piedras, Río Chotepe and Río Chamelecón. In order to efficiently model the effects of flooding for certain events, it was necessary to distribute the rivers of interest into several models. The achievement of results with a high spatial resolution, for a region of interest of this extent, was only possible by the division of the area into three separate models. Río Blanco, Rio Chotepe and Rio Chamelecón. This decision was based on the different catchment extents and the locations of the areas of interests, as well as total number of cells and the resulting computational costs of each model.

For Río Chamelecón, the planned hydropower reservoir “El Tablón” was implemented in the model by considering the resulting changes in discharge. Discharge values were calculated based on the framework of dam planning provided by San Pedro Sula Municipality. Future scenarios were developed on the basis of the mentioned RCA4 Model. RCA4 provides the daily precipitation with a spatial resolution of about 50 km for past and future scenarios. RCA4-was calculating the defined past period (1950 - 2005) and the future period (2005 – 2100). The precipitation change between both of them were analysed and taken via a precipitation factor to the available precipitation statistics of the FIHS and applied to the hydrological models as precipitation input.

2.2.3 Validation

2.2.3.1 Hydrologic Model

Because of the data availability and the general lack of measurement data (e.g. precipitation, runoff, infiltration), the validation of the results was based on the knowledge of local authorities, a plausibility check with literature (USGS, 2002), the Creager envelope curves for extreme floods as well as the results out of the hydrodynamic modelling. The results of the hydrodynamic modelling will be discussed later on. Rio Chamelecón is the most noted catchment, addressed by the USGS Paper (2002).

Validation was therefore possible with restriction against the Creager-Equation (HQ50) and the USGS Paper, analysing the storm event Mitch (USGS 2002). Referenced values are highly different and strongly varying over available studies. The USGS study examined the station Chamelecón el Puente and defined the station as not reliable and deals with the corresponding values carefully. They also carried out a Drainage area relation for the peak flow estimation, calculating a QHQ50 = 2 400 m^3/s whereas based on the statistical analysis QHQ50 measures 1 070 – 2 060 m^3/s. The often-referenced gauge “Chamelecón en puente” is located around 20 km upstream of the analysed model output of this study.

2.2.3.2 Flood Model

Due to scarce data availability, a validation of the hydraulic model results was not feasible. Similarly, a sound validation of the results against the flood event caused by Mitch in 1998 was impossible, due to a lack of available discharge and flood extend data at the time of the study.

The model results were therefore validated on the base of previous studies carried out by local and international organisations such as USGS (2002), COPECO (2016a, 2016b) as well as more recently by Abrego Suárez (2019). Existing 1D model results from these studies as aligned with the improved 2D results of this study. In addition, experts from different governmental offices from the Municipality confirmed the validity of the parameters and assumption made for the calibration of the different models, through a series of calls. The results of the hydrological model described before are used as input for the hydrodynamic modelling. In other words, the hydrographs resulting from the HEC-HMS model, provided therefore the boundaries of the hydrodynamic HEC-RAS model. Because of the data availability and the general lack of observed data (e.g. precipitation, runoff, infiltration), limited statistical validation was possible (Creager envelope curves for extreme floods), expert knowledge and literature review of previous studies.

Comparisons of 50-year flood discharges estimated by different studies and estimates of peak flows during Hurricane Mitch at four municipalities in Honduras shows a strong agreement with the flood model output[7]. At the "Rio Chamelecón en Puente" gauge, located 20km upstream of the Chamelecón catchment outlet, the relation estimated a 50-year flood discharge of 2 485 m3/s and verified this figure with an application of a unit hydrograph model using SCS (Soil Conservation Service, now called the Natural Resources Conservation Service) loss rate parameters to compute a 50-year flood discharge of 2 473 m3/s (Consorcio Lahmeyer International, 1998, p.3-78)[8]. Nevertheless, in the absence of historical discharge gauge, the USGS study indicates peak flows at the outlet ranging of 1 070 - 2 400 m^3/s. A careful Creager envelope curves for extreme events was therefore carried out.

Envelope curves are important tools for the evaluation of floods and for determining the peak discharge in ungauged watersheds. These curves, associated with a mathematical equation, determine the upper line that involves the maximum values of the floods associated with the respective basin areas. The outcomes of this analysis are in close agreement with the discharge simulated for the 50-year flood discharge for the Chamelecon outlet, 1 792 m3/s (Greager 1 475m3/s)[9].

2.3 Results

The HEC-HMS and HEC-RAS models offer a 2D hydraulic simulations of maximum flood extents and water depth, both used as input data in CLIMADA. Results are calculated for three different periods and two climate scenarios. In this section we present only a selection of the results for the sake of clarity. Additional maps are presented in ANNEX 2 for the three return periods (TR25, TR50, TR100) and the different scenarios (present, future high and future low).

The general results show an increase of the flood extend over SPS in simulations with future climate signal. Figure 2 shows a strong climate signal (RCP8.5) returning a larger flood zone especially in the southern part of the city (Rio Chamelecón), but also alongside the Rio Chotepe. More elevated areas (in the northern part of San Pedro Sula) remain unaffected by a change in climate signal, where only the riverbed is affected, with partial flooding of the river banks.

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[7] USGS: US Arma Corps of Engineers - Hydrologic Engineering Center. (2002): Flood-Hazard Mapping in Honduras in Response to Hurricane Mitch. Water-Resources Investigations Report 01-4277.

[8] Consorcio Lahmeyer International, 1998, Estudio de factibilidad y diseño final proyecto obras prioritarias en zonas de alto riesgo, Chamelecón Pueblo-Choloma: Report prepared for Gobierno de Honduras, Comisión Ejecutiva Valle de Sula.

[9] USGS: US Arma Corps of Engineers - Hydrologic Engineering Center. (2002): Flood-Hazard Mapping in Honduras in Response to Hurricane Mitch. Water-Resources Investigations Report 01-4277.

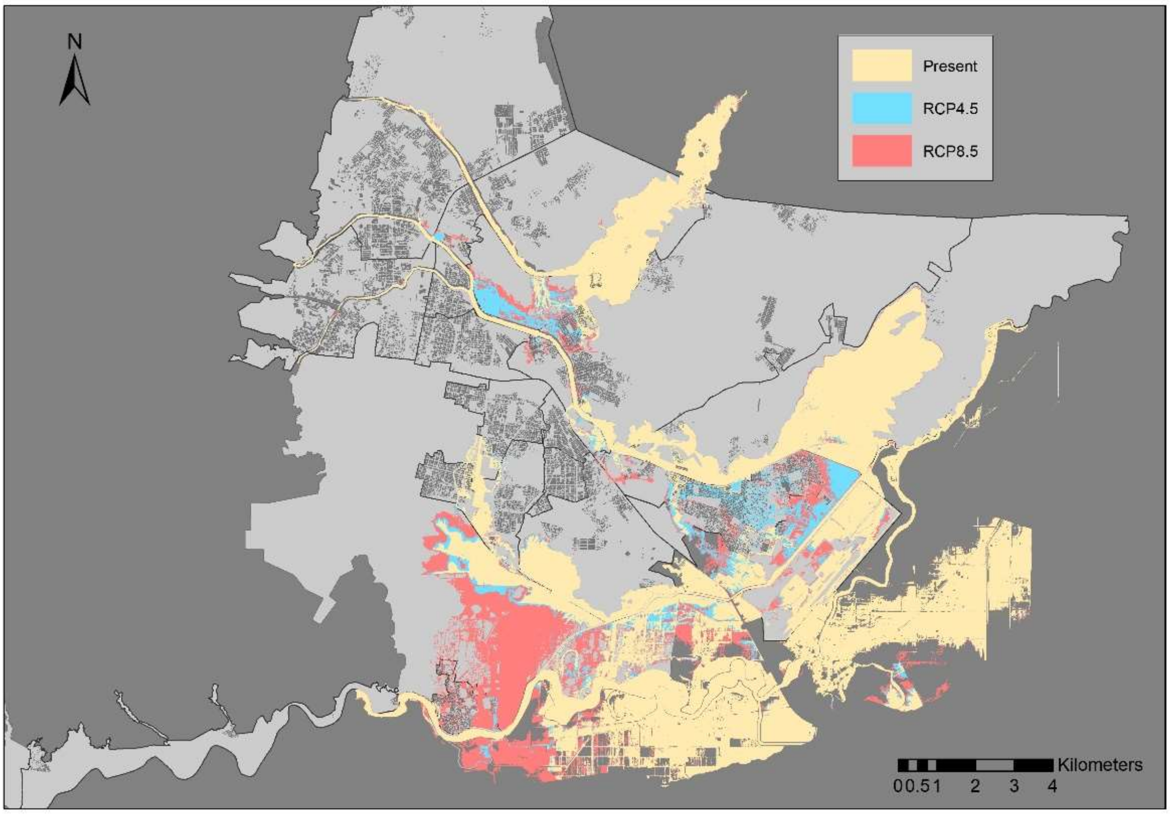

Figure 2 Flood extend for the three different scenarios modelled for the 100yr return period (present, RCP 4.5 and RCP 8.5 scenarios)

Water depth, equally as flood extend are an important input to CLIMADA. We present a selection of results for today's climate and a future scenario, both for large flood events (100yr). For an easier understanding, water depths are classified into three classes. These three classes are determined by the severity of an invent intensity.

- Water depth < 1 m = "low" severity of exposure
- Water depth 1 - 2 m = "medium" severity of exposure
- Water depth > 2 m = "high" severity of exposure

Figure 3 shows three classes of water depths for large floods (100yr) for today's climate. Figure 4 presents the same classes for a strong future climate scenarios (RCP8.5) for large floods (100yr) in the municipality of SPS. It depicts a significant increase in areas suffering from higher water depths values, suggesting larger damages in these areas. In addition, as discussed before, for a strong climate signal, the overall flooded areas is also expected to increase.

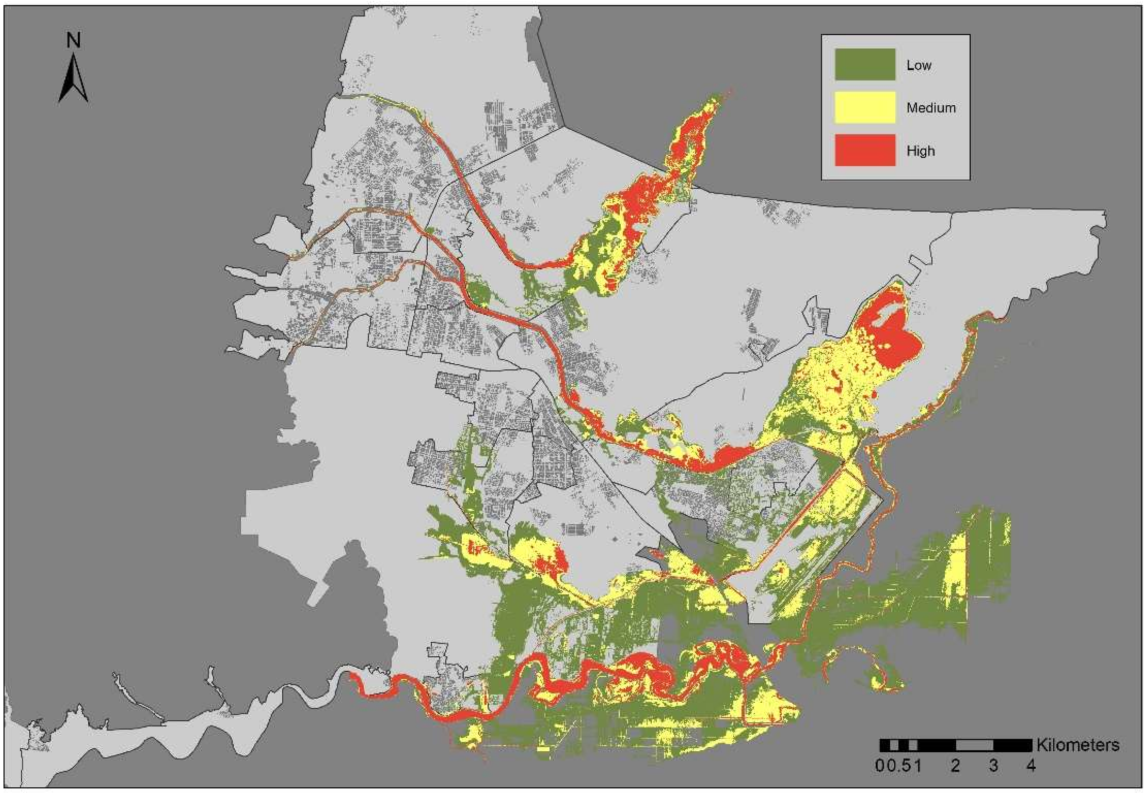

Figure 3 Maximum water depth for the present climate (100yr)

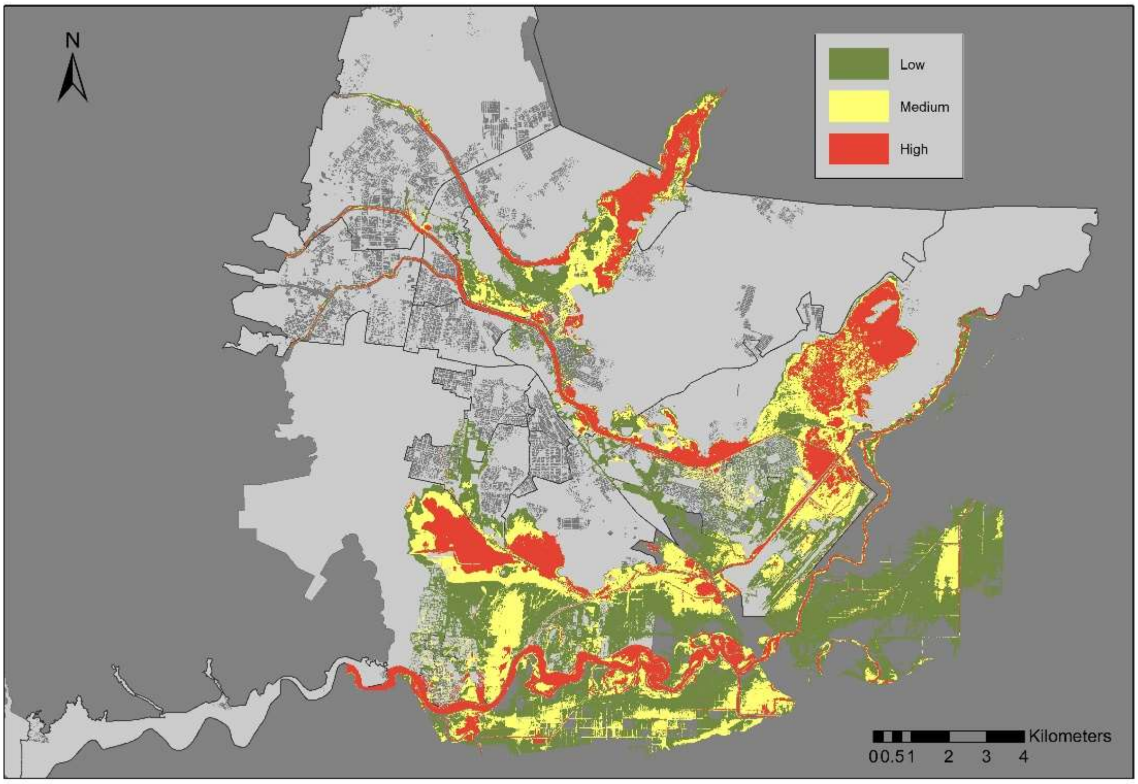

Figure 4 Maximum water depths for an RCP 8.5 scenario (100yr)

Further, we explore the possible impact of the hydropower dam el Tablón (in planning) located in the catchment of the Chamelecón. These results are based on information available to date (further explained in Chapter 7.3 Recommendation for el Tablón) and might change depending on the location and the final dimension of the dam. However, they provide useful insight for decision regarding further planning. Figure 5 shows the simulated flood extend of flood events for different inundation frequencies (25yr, 50yr, 100yr). The dam shows a noticeable effect on the flood extend in the municipality area, however, with a stronger impact for lower intensity events (25yr and 50yr return) as displayed in Figure 6.

However, with the parameters considered here, flood damage to the airport and other low land areas in the vicinity of the Chamelecón River are still expected to be impacted severely by flood events of large intensity. Possibly, a careful dimensioning of the future project should take place in order to account for the mitigation of stronger flood events.

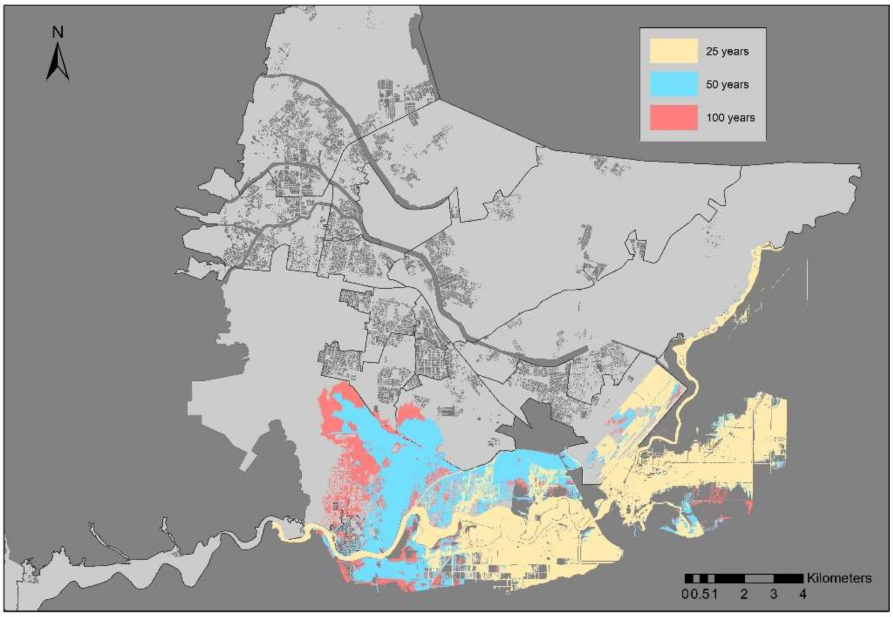

Figure 5 Impact of El Tablón Dam on flood extend for large flood in the Chamelecón sub-catchment

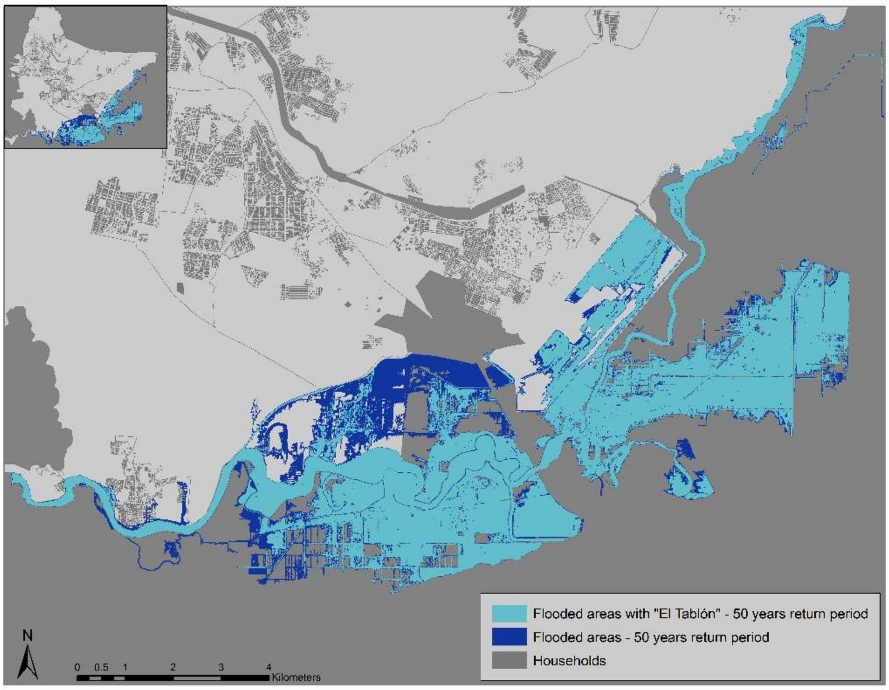

Figure 6 Impact of el Tablón Dam for the RCP4.5 future scenario (50Yr)

2.4 Limitations and Conclusion

This sections present the methods, data and parameters used for the setup of the hydrological and hydraulic models for the municipality of San Pedro Sula. This new set up constitute a significant advance in terms of flood modelling in the region. Nevertheless, an honest and careful discussion regarding limitation and uncertainties linked with the forecasting exercise is necessary to further improve future iteration of the model.

Uncertainties within hydrodynamic modelling generally arose due to the quality of the DEM in some regions. Artefacts, presumably sourcing from data recording as well as from vegetation, were present throughout the whole project area without possibilities for improvement. During the implementation of the river channels in the hydraulic models, several assumptions were made, deflecting real conditions. Uncertainty also arose in the construction of the river channel, since cross sections were not measured but obtained from the DEM. Measured cross sections would have provided a higher accuracy, leading to better results. Additionally, there are several bridges in the area of San Pedro Sula, of which only two were considered. Possible backwater effects could therefore not be taken into account.

Another major source of uncertainty lies in the lack of discharge data. To date, no reliable discharge data exist and this model is based on statistical extrapolation techniques and expert knowledge only. We will come back with recommendations on these aspects later on in this report. Reliable discharge and water level stations are key to a better monitoring, early waring and forecasting of floods in the region.

Precipitation data used in the study constitute also an additional source of uncertainty. Indeed, station data comes with limitations and requires extrapolation technique. For terrains with strong elevation changes, such as in the Sulla Valley, these techniques have a limited validity. Here too, further development of the station network, possibly in combination with remote sensing would improve the reliability of precipitation data.

Finally, climate scenarios, GCM and downscaled data offer a series of bias due to resolution, orographic changes and temporal issues which impairs the forecasting power of flood models in general. In conclusion, the outputs of the study included inundation depth and flood extents for three return periods (10, 50 and 100 years) for the present and the future (RCP4.5 and RCP8.5). In comparison with existing flood model such as the 1D study from COPECO (2016)[10] and Abrego Suarez (2019)[11], significant improvements have been made, in terms of DEM correction, enhancement of details concerning spatial resolution as well as the introduction of several climate scenarios. Finally, the uncertainties considered in this section reflect the challenges existing in data scare regions. Such challenges are intrinsic to any flood modelling. Henceforth, the results of the 2D SPS flood model are explicitly fit for purpose for the scope of this study and, beyond, are also to be considered for a basis to further planning in the region of San Pedro Sula.

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[10] COPECO: Comisión permanente de contingencias. (2016a). Informe V- Hidrología, Producto 1. Análisis de Riesgo a nivel municipal y local, Estimación de Avenidas – Sistemas de cuencas del Municipio de San Pedro Sula Departamento de Cortés. San Pedro Sula.

[11] Abrego Suárez, C. R. (2019). Actualización preliminar de los umbrales de alerta por inundación de Río Chamelecón en ciudad La Lima, Cortés, para el período de observaciones 2010-2018. Tegucigalpa, Honduras.: Master Thesis.

3 ASSET VALUATION

3.1 Background and Methodology

The following chapter describes how the different types of assets and their values were estimated. CLIMADA relies on georeferenced data and hence, both, risk scenarios and damage to assets, have to be simulated based on georeferenced information. Therefore all assets were previously geo-located and partitioned where necessary as described in further detail in the corresponding subchapters below.

The following is an overview of the methodologies used in this study to estimate asset values:

- Field surveys: especially with regard to vulnerable population, Los Bordos, and housing,
- Discussions with experts: facilitated through the project's focal person at the Municipality of San Pedro Sula
- Estimation of real estate owned: based on available cadastre data[12]
- Assessment of characteristic and relevant infrastructure and public assets

In addition to the data available online and the data provided by the Municipality, a survey was implemented on the household level in the selected district in order to gain further insights into people's living condition. Data was gathered in reference to households' wealth, income levels, as well as the level of affectation during previous flood events, e.g. affected people and experienced damages on their assets. This survey was implemented by Department of Municipal Research and Statistics of San Pedro Sula (*Departamento de Investigación y Estadística Municipal*, DIEM).[13]

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[12] During the data validation webinar values based on the cadastre estimates were presented for all asset sub-categories that involve buildings. Several participants objected to those values as some of them may be outdated and the year, and hence the corresponding USD exchange rate, are not recorded. During some follow-up discussions facilitated by the Municipality's focal person for the study several experts provided the UNU-EHS team with updated estimates which were then applied and compared. In most cases (Educational and Health Facilities, and Electrical Infrastructure) the changes to the overall sum of the respective asset sub- category did not change significantly. However, in the case of heritage sites, roads as well as airport taxi- and runways the value increased majorly due to the changes. For electric substations the updated estimate based on official project cost estimates reduced significantly. After detailed discussions it was confirmed that those updated values estimates should be applied as those are officially used for planning.

[13] The field survey will from now on referred to as DIEM (2020) when making reference to any of the obtained data and results. The methodological framework of the survey can be found in ANNEX 3.

3.2 Assets Categories

The assets examined in this study were confirmed during an iterative process through (a) the inception workshop and the corresponding report and (b) indirectly through the validation webinar and its report. Although the importance of the drainage and sewage systems are recognised it was decided that due to a lack of data about its state and characteristics the asset 'Drainage' should only cover natural streams and major canals. However, following that line, the drainage system is still considered in the list of potential measures.

Hence, the list of assets and its sub-categories as defined for the analysis are the following:

1. Vulnerable People
2. Informal Settlements (Housing in *Los Bordos*)
3. Housing
    a. Low quality buildings of one story
    b. Medium quality buildings of one story
    c. Medium quality buildings of two or more stories
    d. High quality buildings of one story
    e. High quality buildings of two or more stories
4. Road Network
    a. Minor roads of one lane
    b. Major roads of two or more lanes
5. Public Buildings
    a. Educational facilities
    b. Health facilities (major hospitals and smaller health facilities)
    c. The Ramón Villeda Morales International Airport
    d. Fire brigades
6. Electrical infrastructure
    a. Low voltage power lines for urban distribution
    b. Primary transmission lines of higher voltage (13.8 and 34.5 kV)
    c. Distribution Substations
7. Drainage (natural streams and major canals)
8. Heritage sites
9. Environmental assets
    a. Green areas, forests and parks
    b. Water bodies

Based on the initial results from literature review and the provided data a data validation webinar was conducted with experts and representatives from the Municipality of San Pedro Sula. During the webinar and during some follow-up discussions recommendations were made regarding the updating and refining of the values for some asset categories.

The following sub-chapters will provide further insights into the respective assets location, the selected valuation method and the valuation results. Monetary values are to be understood in 2020 USD terms although challenges in applying the most appropriate exchange rates were faced due to some datasets not recording the date of data collection. The chapter will be concluded with an overview of all the assets in the study region.

3.3 Vulnerable People

The definition of vulnerable people is based on the Intergovernmental Panel on Climate Change (IPCC)[14] which includes the following three main components of vulnerability:

- exposure,
- adaptive capacity
- and sensitivity.

To account for **exposure**, and in line with the guidelines of the IPCC, we inventoried populations living in areas with high flood hazard according to the results from the model described in Chapter 2. Figure 7 shows the areas that are exposed to floods following the footprint of a 50-year event (return period). To address the inhomogeneous delineation a 100m buffer was included.

Adaptive capacity, hence the ability of a system to cope, is being approximated by the percentage of households with unsatisfied basic needs (*Necesidades Básicas Insatisfechas,* NBI)[15] within neighbourhoods. To distinguish between 'vulnerable population' and 'population' in general a cut-off at 30% none unsatisfied basic needs was chosen (0NBI<=30%). In other words, when more than 70% of the households of a given neighbourhood have at least one basic need unsatisfied, the neighbourhood is considered with low adaptive capacity and therefore vulnerable. By definition, all inhabitants of *Los Bordos* were considered as vulnerable.

Finally, **sensitivity**, the degree a system is being affected in case of floods, will be defined by the modelling exercise using CLIMADA.

In order to estimate the number of potentially affected people in each house, including those in *Los Bordos*, a random number of inhabitants was assigned to each household. The random values were generated through a truncated Poisson distribution with values between 1 and 12 and a mean of 4.0 persons per household, based on statistics provided by the Municipality[16].

Figure 7 highlights both, the 'vulnerable population', those households being exposed and living in a neighbourhood of NBI<=30% in red, and further 'exposed' population groups that are exposed to flooding but live in areas of higher basic needs satisfaction. Table 1 summarises the estimated population living in the study area as well as the subgroups of vulnerable and exposed population. For comparison reasons, Figure 8 presents the same applying the foot print of a 100 year return period event.

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[14] IPCC (2014) *Climate Change 2014. Impact, adaptation and vulnerability*. Part A: Global and sectoral Aspects Working Group (WG) II Report

[15] The NBI is an index that was developed in the 1960s and that was adopted by the UNECLAC (United Nations Economic Commission for Latin America and the Caribbean) for poverty monitoring and benchmarking within the region in the 1980s. The four basic needs categories considered by the NBI are: 1) Access to housing, which measures the quality of housing and level of overcrowding, 2) Access to sanitary services, defined as the availability of drinking water and the type of excreta disposal system in the household, 3) Access to education, in terms of attendance of children at school-age to an educational establishment, and 4) Economic capacity, measured as the probability of insufficient household income at any given time. For further details see: Feres, Mancero, (2001). *El método de las necesidades básicas insatisfechas (NBI) y sus aplicaciones en América Latina*. Retrieved from: https://www.cepal.org/es/publicaciones/4784-metodo-necesidades-basicas-insatisfechas-nbi-sus-aplicaciones-america-latina

[16] The value 4.0 persons per household is based on: Secretaría de Salud [Honduras], Instituto Nacional de Estadística (INE) e ICF International. (2013). *Encuesta Nacional de Salud y Demografía 2011-2012*. Tegucigalpa, Honduras: SS, INE e ICF International.

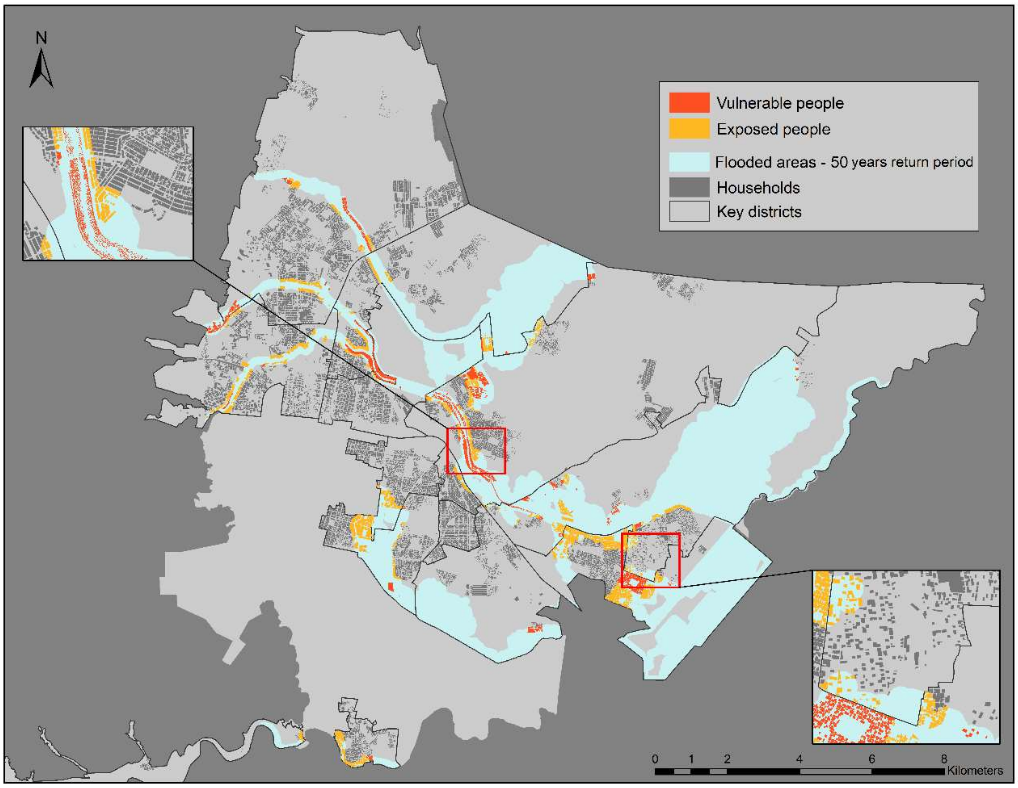

Figure 7 Households exposed to floods for a 50 years return period at the present scenario. Red: Households defined as vulnerable based on their exposure and an NBI value below 30%, Orange: Households being exposed but with an NBI value above 30%. - Source: Authors' own compilation

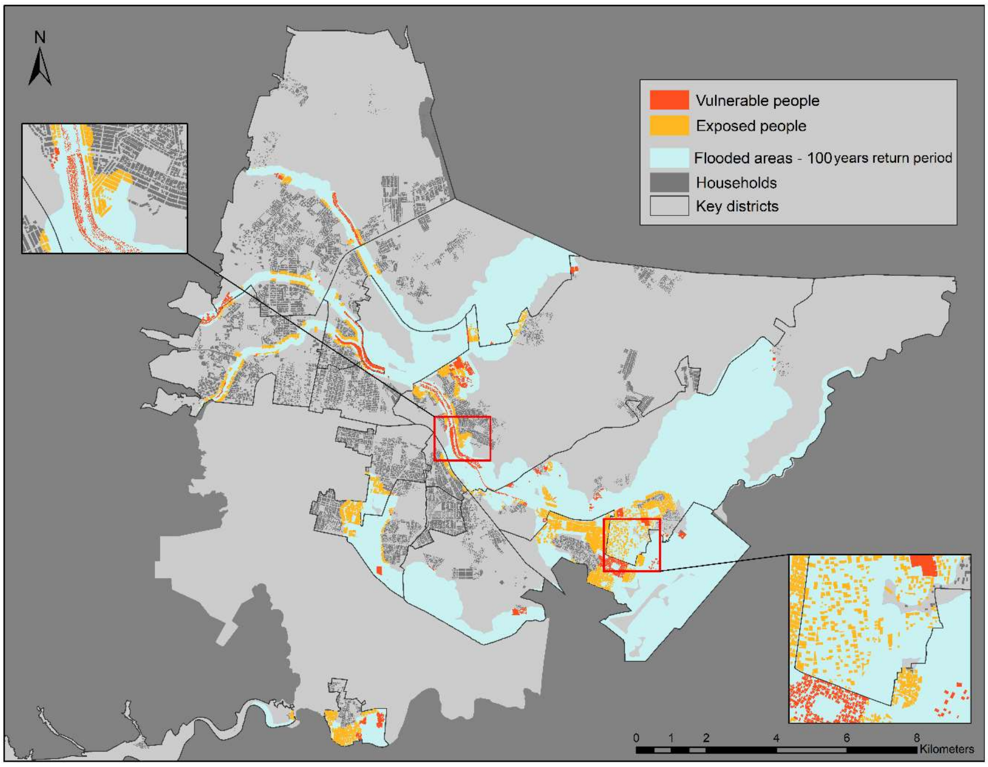

Figure 8 Households exposed to floods for a 100 years return period at the present scenario. Red: Households defined as vulnerable based on their exposure and an NBI value below 30%, Orange: Households being exposed but with an NBI value above 30%. - Source: Authors' own compilation

Table 1 (Vulnerable) Population estimates (based on a 50 year return period)

	Number of households (% of total)	Total number of people (%of total)
Los Bordos	6 778	27 685
Formal Settlements, total	71 915	293 582
Total Vulnerable Population (Red)	7 603 (9.7%)	30 622 (9.5%)
Exposed Population (Orange)	8 368 (11.6%)	34 168 (11.6%)

3.4 Informal Settlements (Los Bordos)

Informal settlements are by definition less closely monitored and hence cadastre data do not provide a solid base for the analysis. The formerly mentioned field survey by DIEM (2020) however took a focus on households in *Los Bordos* and did provide some information on the location, quality and value of housing as well as experienced losses in three past flood events.

3.4.1 Location

The baseline for the locations of the houses were the sample of surveyed households (700) which included locations and were directly mapped by the Municipality. Since little other information was available, including reliable satellite imagery, for each family[17] a dwelling was randomly generated within the respective boundaries of the *Los Bordos* district which were provided by the Municipality of San Pedro Sula on household density data for each *Bordo*. It is assumed, based on the survey results, that houses generally do not have multiple stories and hence all families live on the ground floor. Although it can be assumed that in some instances more than one family may live in a single house for simplicity reasons each family is represented by an individual house.

Figure 9 below showcases the location and value estimates of housing while rectangles depict actually surveyed houses and circles represent randomly generated houses.

[17] The number of families per *Los Bordos* district was provided by experts of the municipality.

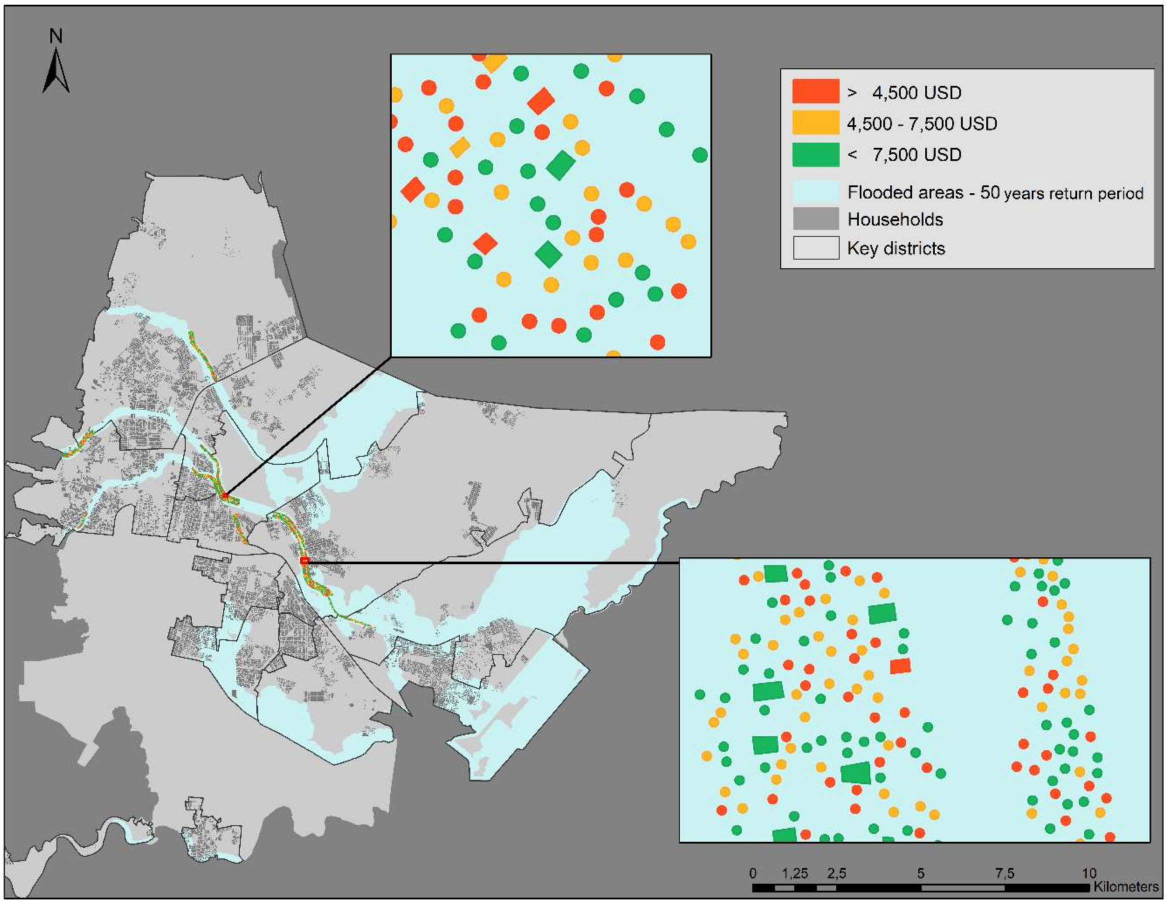

Figure 9 Location and USD value estimates of housing in Los Bordos - Source: Authors' own compilation

3.4.2 Values Estimation

Using the results from the survey, specifically the information on wall and floor material and conditions, a score on building quality was developed and employed as value indicator. Ranging between 0.1155 and 1, the magnitude of the score gets higher as the materials and quality of walls and floor are better[18]. Scores were assigned randomly to the newly generated dwellings[19] applying the same distribution pattern as observed in the 310 surveyed houses. Figure 9 illustrates the random distribution.

A maximum housing value of 5 000 USD was estimated and confirmed during the data validation webinar for a dwelling, it was assigned to the higher score and was proportionally reduced for dwellings with lower scores, i.e. the minimum score corresponds to a value of 577.5 USD. The interior value of the houses, household assets, were also estimated based on the score, assuming that a family who can afford a better quality housing could also afford more and better quality furniture and appliances. Here a maximum value of 5 300 USD was assigned to the higher score and lower scores received proportionally lower values, i.e. the minimum score was assigned a value of 612.15 USD.

[18] Scales and procedure can be found in ANNEX 4 - Valuation of housing in Los Bordos

[19] See chapter 3.2.1 Location for further details

Table 2 Value range and total value estimates for housing in Los Bordos

	No of households	Housing value (USD)	Household asset's value (USD)	Total (USD)
Ranges		577.5 - 5 000	612.15 - 5 300	1 189.65 - 10 300
Estimated total	6 778	19 891 905	21 085 419	40 977 324

3.5 Housing

3.5.1 Location

Just as informal housing, formal housing is one of the key assets of the ECA framework. Other than in the case of housing in Los Bordos, the city's cadastre provides valuable information on location, size and value of buildings and plots. The datasets shared had some limitations, one related to the data updating process that is currently on-going in the Municipality, rendering some values non-representative of the current conditions of the buildings, and another one related to data gaps, with some datasets being more commonly absent like constructed areas.

All considered, buildings identified by the Municipality as no-habitational and those with constructed areas equal or less than 20% of the plot[20] were not considered for this study. Figure 10 illustrates the considered buildings and their total values.

[20] Following a comparison of satellite images and the cadastre data it was realised that buildings smaller than 20% of the plot in most cases were buildings such as guard houses on parking lots or work/ garden sheds in e.g. parks or rather un-representatively large properties.
Buildings with no data on constructed area were validated using satellite images.

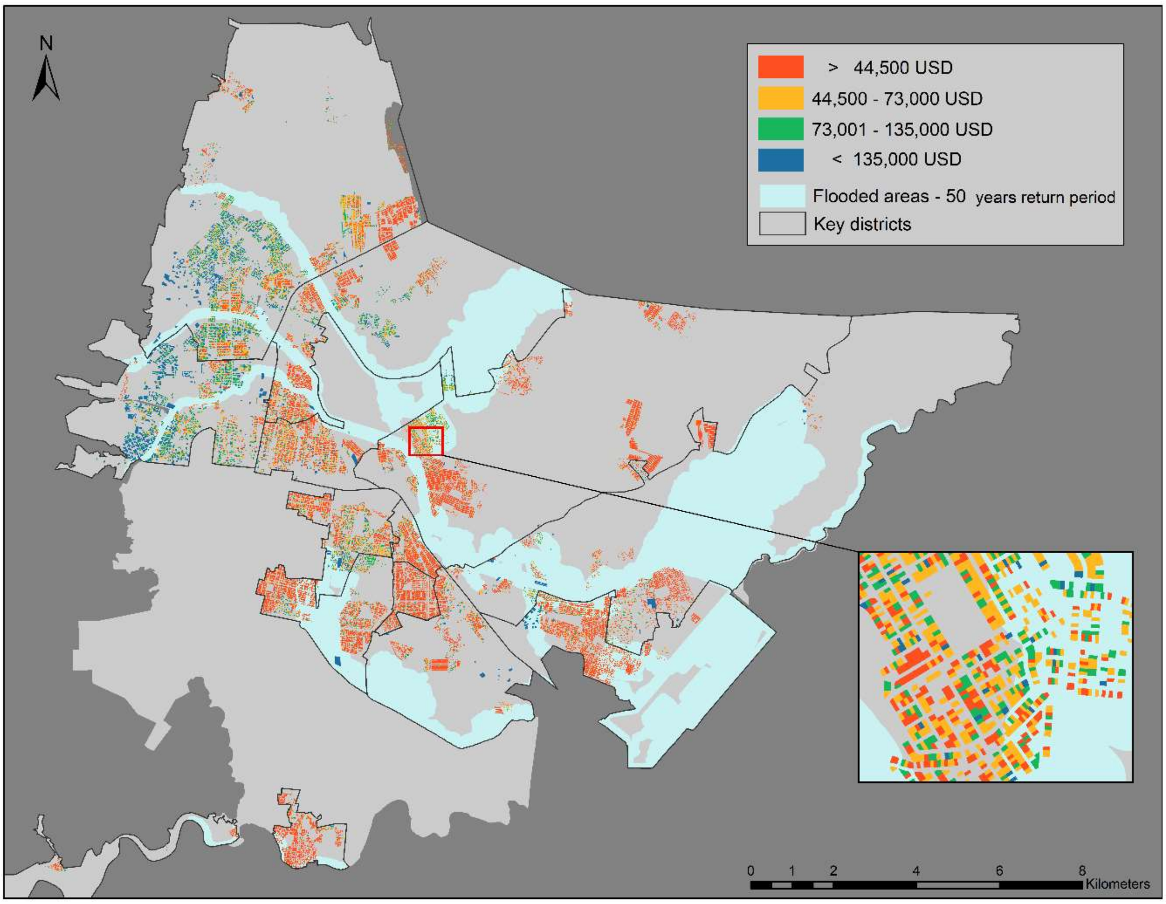

Figure 10 Estimated 2020 USD values for formal housing in San Pedro Sula. Source: Authors' own compilation

3.5.2 Values Estimation

In order to estimate the value of people's housing and the corresponding condition two factors are being recognised. First, the construction value as registered in the cadastre data. And secondly, the household assets in the house, i.e. appliances and furniture.

As there were no reliable data available for interior values, assumptions were made based on two factors. 1) The basic unsatisfied needs index (NBI)[21], which was used as a general wealth indicator, and 2) whether a building has one or more than one story. In case a house has multiple stories a higher standard of living was assumed in comparison to the one-story buildings in the same NBI range. Three NBI ranges (low: <30%, medium: 30-60%, high >60%) were defined. Following this procedure results were classified into five final categories (for all buildings in the NBI range below 30% only one story was assumed), each being assigned a value estimate per m^2 based on regional estimates and confirmed using both, expert interviews and the data obtained through the household survey by DIEM (2020), as presented in Table 3 below.

Table 3 Per square meter value estimates for different classes of housing

NBI range and No. stories	USD per m^2
< 30%, one story	151.43

[21] In this case we used the 0NBI index measured by the Municipality. This presents the percentage of households in a given neighborhood that have all of their basic needs satisfied. Further details of the basic needs studied are presented in footnotes of the first page of chapter 3.3 Vulnerable People

30 – 60%, one story	178.75
30 – 60%, two or more stories	182
=> 60%, one story	254
=> 60%, two or more stories	271.1

Based on the above described methodology and prices, the results are summarized as follows.

Table 4 Housing valuation summary

	No of houses	Average total value in USD	Total in USD
Low	11 099	41 507	460 686 195
Medium	20 965	43 840	919 102 206
High	39 851	53 610	2 136 412 468
Total	71 915	48 893	3 516 200 870

3.6 Road Network

In order to reflect the existence of different roads the Municipality's road network was divided into two different sub-classes, namely *minor roads* of just one lane and *major roads* of two or more lanes. Local experts in the aftermath of the data validation webinar shared estimates used for planning road construction of 2 580 HNL/m^2 (≈ 114.92 USD/m^2). Following an analysis of cross sections of some example roads as outlined in the supporting documents of the Municipality's Development Master Plan (PMDM) a width of 7m for minor roads and 15m for major roads is assumed resulting in the following estimates in Table 5; Figure 11 displays the road network considered in this study.

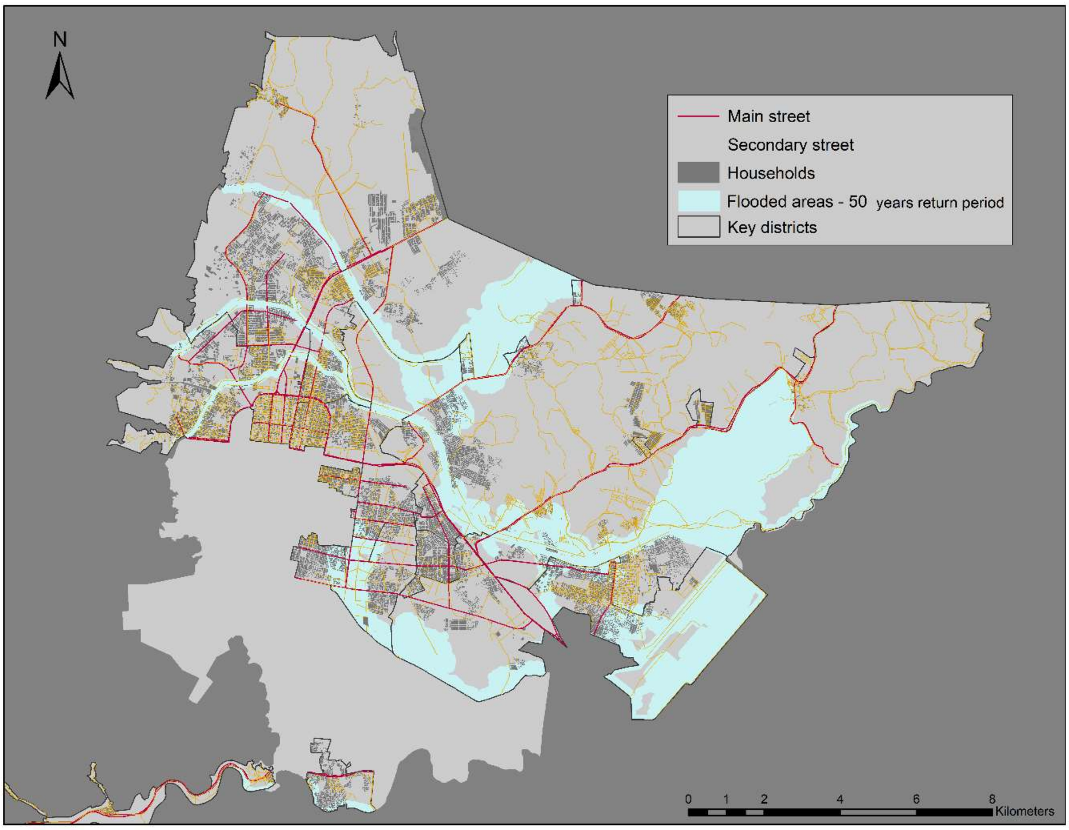

Figure 11 Considered road network. Red: Major roads. Yellow: Minor roads. Source: Authors' own compilation.

Table 5 Road value estimates

	Total length (m)	Total area (m²)	Price (USD/m²)	Total (USD)
Minor roads (7m wide)	780 158	5 461 108	115	627,590,507.43
Major roads (15m wide)	188 036	2 820 534	115	324,135,731.79
Roads Total		**8 281 641**	**115**	**951,726,239.22**

3.7 Public Buildings

In the category of public buildings several different types are being recognised. Those are namely educational facilities, health facilities, and fire brigades. Within the districts in the Municipality selected in the inception and data base workshops (districts 1,2,3,4,7,10,11,12,13,14,15,16,18), the comprehensive cadastre records provided 23 health facilities of different size ("hospitals" and "smaller health centres"), 100 educational facilities, 4 fire brigades, and the Ramón Villeda Morales International Airport were identified.

Figure 12 displays the location of each type of assets in this category. The location and size of the buildings again is drawn from the cadastre files provided.

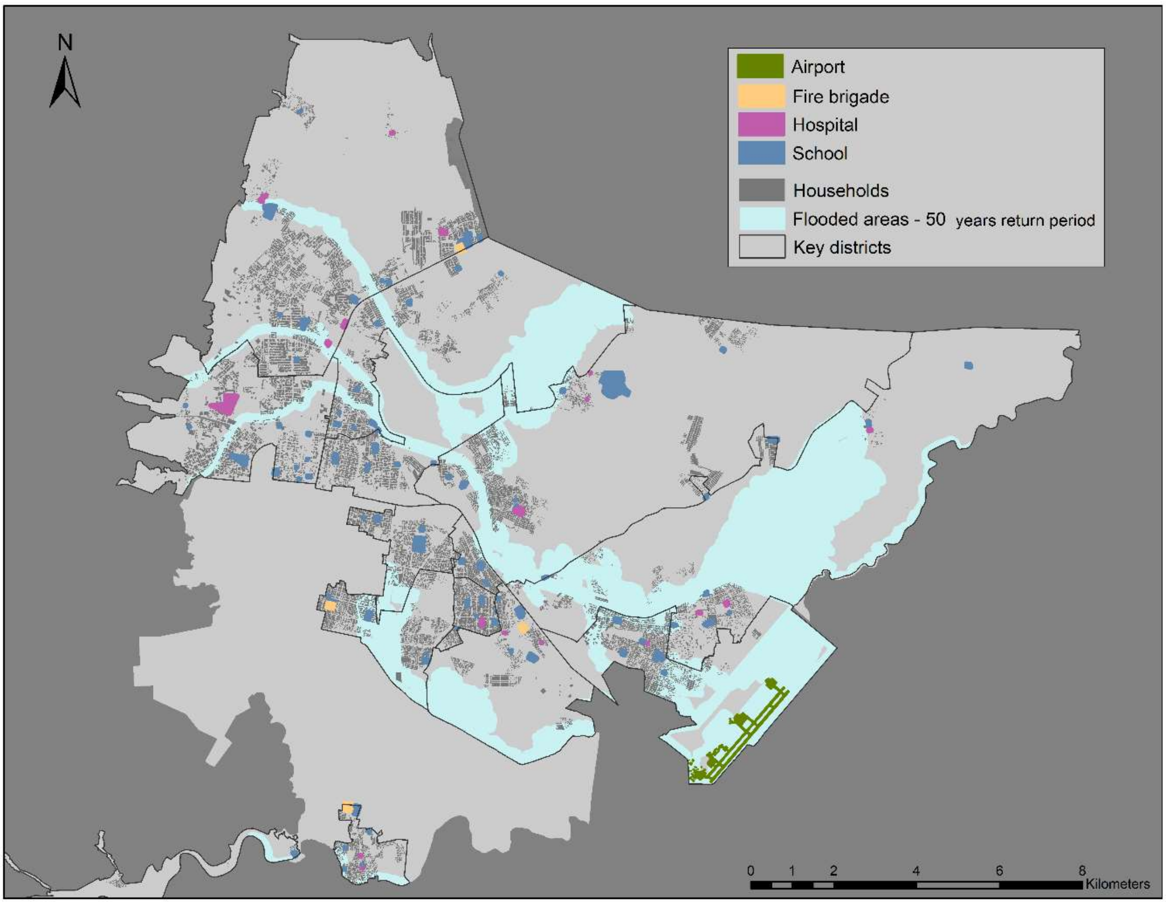

Figure 12 Location of public buildings studied. Source: Authors' own compilation.

In the following sections the different valuation methods employed for the asset sub-categories is being outlined.

3.7.1 Health Facilities

For the 23 health facilities within the selected districts (presented in purple in Figure 12) both construction value as well as the value of the medical equipment and furniture is likely to be damaged by a flood, hence the potential basements and the ground floor of hospitals and health centres are considered. With regard to the structural component, the values provided by the cadastre were updated following the data validation webinar that took place on August 26, 2020, were representative experts suggested the values typically used for planning and tenders purposes (28 635 HNL/m^2 ≈ 1 154.64 USD/m^2). As the result of this study shall serve to make investment decision and hence fit right into the Municipality's planning, this value was deemed most appropriate.

As for the equipment, no estimate for values were made available by the Municipality. The values used are based on a UN-ECLAC[22] report analysing the flood damages on hospitals and smaller health centres caused by Hurricane Mitch. The cost to refurnish and re-equip hospitals differ substantially depending of the size of the health centre: refurnishing and re-equipping larger hospitals is estimated at about 9m USD per hospital (national or regional) while for smaller health centres 180 000 USD per facility. A synthesis of the used values is outlined in Table 6.

Table 6 Value estimates for hospital and health centres

	Number	(Re-)Construction Value USD/m^2	Refurnishing USD/unit	Total USD
Hospital	2	1 155	9 000 000	169 236 634
Smaller health centre	21	1 155	180 000	113 535 293
Health facilities total	**23**			**282 771 928**

3.7.2 Educational Facilities

In the same fashion as for the health facilities, for the 100 educational facilities (presented in blue in Figure 12) values for the buildings' structure are based on the Municipality's estimates for planning and tenders (9 000 HNL/m^2 ≈ 362.9 USD/m^2). For estimating refurnishing costs again the UN-ECLAC report on damages caused by Hurricane Mitch is being employed revealing an estimate of 20 USD/m^2 based on damages occurred and the number of affected classrooms. Table 7 summarises the value estimates for educational facilities.

Table 7 Educational facility value estimates

	Number	(Re-)Construction Value USD/m^2	Refurnishing USD/m^2	Total USD
Educational centres	100	362.9	20	356 456 521

3.7.3 Ramón Villeda Morales International Airport

The Ramón Villeda Morales International Airport (presented in green in Figure 12) is located to the east of San Pedro Sula and lies at 27 MAMSL close to the Chamelecon River facing high flood risk.

The value of the buildings of the airport depend on several different components, i.e. internal and external structures, furniture and sanitary/ disposal fittings, heating and air-conditioning units, as well

[22] UN Economic Commission for Latin America and the Caribbean. (1999). Honduras: Assessment of the Damage Caused by Hurricane Mitch, 1998. Implications for economic and social development and the environment.

as electrical, communications and protective installations resulting in roughly 3 678 USD/m^2 which can be estimated as displayed in Table 8.[23]

The only runway of the airport is approximately 2 900m long and 44m wide with a concrete surface. Following the data validation webinar and the presentation of taxi- and runway cost estimates, local experts recommended to use the same estimates as were applied for roads (114.92 USD/m^2) resulting in the values presented in Table 8 with the areas being based again on the Municipality's cadastre data.

Table 8 Cost estimates for Ramón Villeda Morales International Airport

	Cost per m^2 (USD)	Area in m^2	Total USD
Buildings	3 678	61 177	225 008 495
Runway	115	127 191	14 616 789
Taxiway	115	299 802	34 453 249
Tarmac sub-total		**426 993**	**49 070 038**
Airport Total			**274 078 533**

3.7.4 Fire Brigades

As fire brigades (presented in yellow in Figure 12) provide vital emergency relieve services during extreme weather events and especially during flood situations, they were taken up too as an asset to be considered. Building values for the four relevant fire brigades for the scope of the study, are based on the values the cadastre data provided by the Municipality. As fire brigades are a rather specific building type very little academic literature targeted at their furnishing is available, the same estimates as for terminal buildings is being applied under the premise that similar construction requirements and standards, such as e.g. security requirements, have to be followed. Hence, a total value of 1,808 USD/m^2 (consisting of furnishing, sanitary fittings, heating and cooling systems, electrical communication, and protective installations) is being applied.

Table 9 Fire Brigades value estimates

	Number	(Re-)Construction Value	Refurnishing	Total USD
Fire Brigades	4	*As per cadastre*	1 808 USD/m^2	1 711 306

3.8 Electrical Infrastructure

The urban electrical grid in San Pedro Sula largely follows the road network and is carried by either wooden or concrete poles overhead. However, there are some primary distribution lines for distribution on a regional level operating at a medium voltage (13.8 and 34.5 kV) while the urban distribution and customer service drop lines operate at low voltage, i.e. less than 4 kV. Major transmission lines at high voltage are not to be found within the study area. Therefore the electric grid network is here split into two separate types:

- Primary distribution lines: operating at medium voltage, in San Pedro Sula either at 34.5kV or 13.8kV
- Urban distribution lines: operating at low voltage (typically <4 kV) for the distribution to households and businesses

Additional to the electrical grid two electrical sub-substations were identified.

[23] IEA Energy Technology Network (2011). *Aviation Infrastructure*. Energy Technology Systems Analysis Programme. Technology Brief T16.

Figure 13 shows the location of the two identified sub-stations within the electric grid according to the two classifications of primary and urban distribution lines.

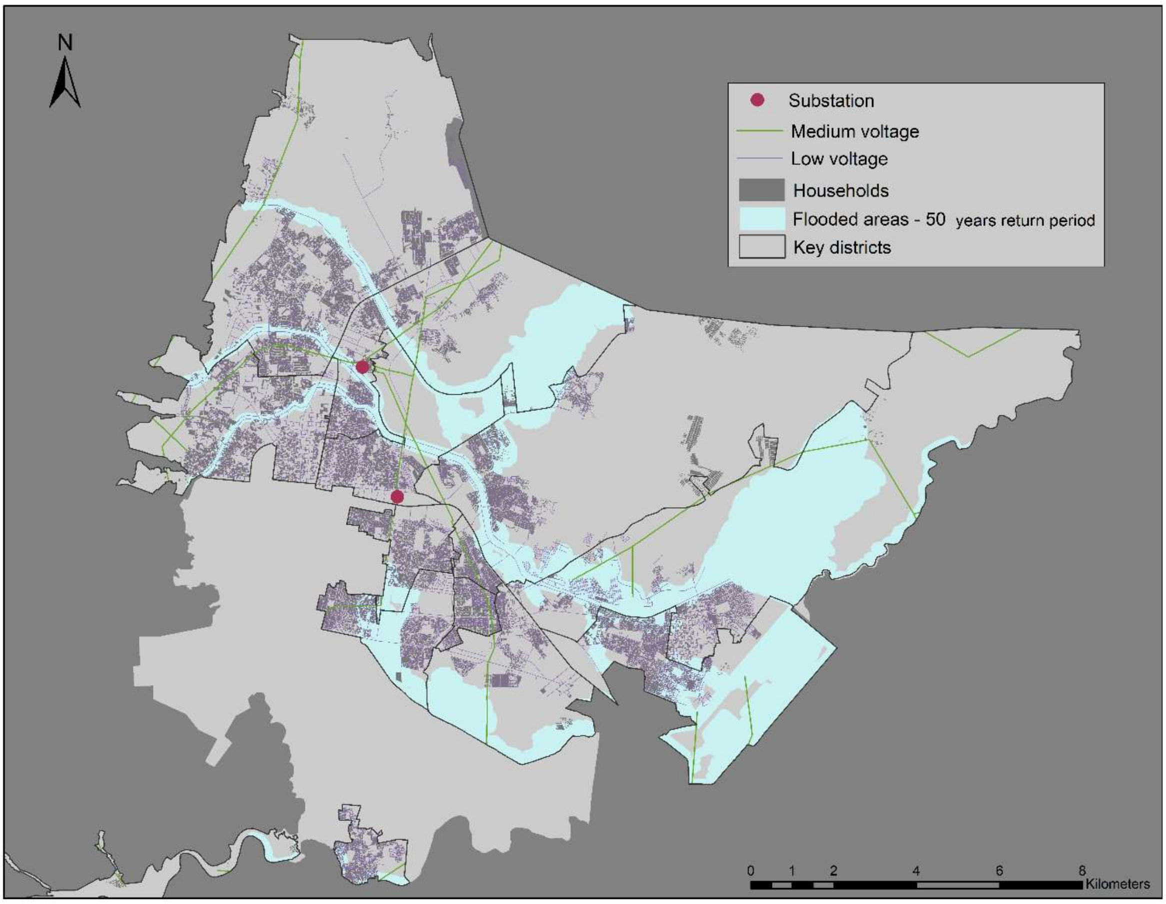

Figure 13 Electrical grid, incl. substations. Source: Authors' own compilation.

For the different types of distribution lines value estimates were provided by local experts with 60 000 USD/km for primary distribution lines and 30 000 USD/km for low-voltage urban distribution lines. The value estimate for the two sub-stations is based on project cost estimates for those and similar sub-stations in and around San Pedro Sula at 625 000 USD per station. Table 10 below summarises the estimates.

Table 10 Electrical Infrastructure values estimates

	Total km	Value estimates in USD/km	Total USD
Primary distribution lines (34.5 and 13.8 kV)	61.39	60 000	3 683 103
Urban distribution lines (low voltage)	1 125.54	30 000	33 766 305
Grid Sub Total	**1 186.93**		**37 449 408**
Substations (USD per unit)	2 stations	625 000 USD/unit	1 250 000
Electrical infrastructure Total			**38 699 408**

3.9 Drainage Channels

As a key system in flood management the natural drainage system, i.e. rivers, are being considered as assets. Namely, relevant parts of the rivers Rio Bermejo, Rio Blanco, Canal Chotepe, and Canal Sauce, are being included with an overall length of 25.33 km within the study area, as displayed in Figure 14.

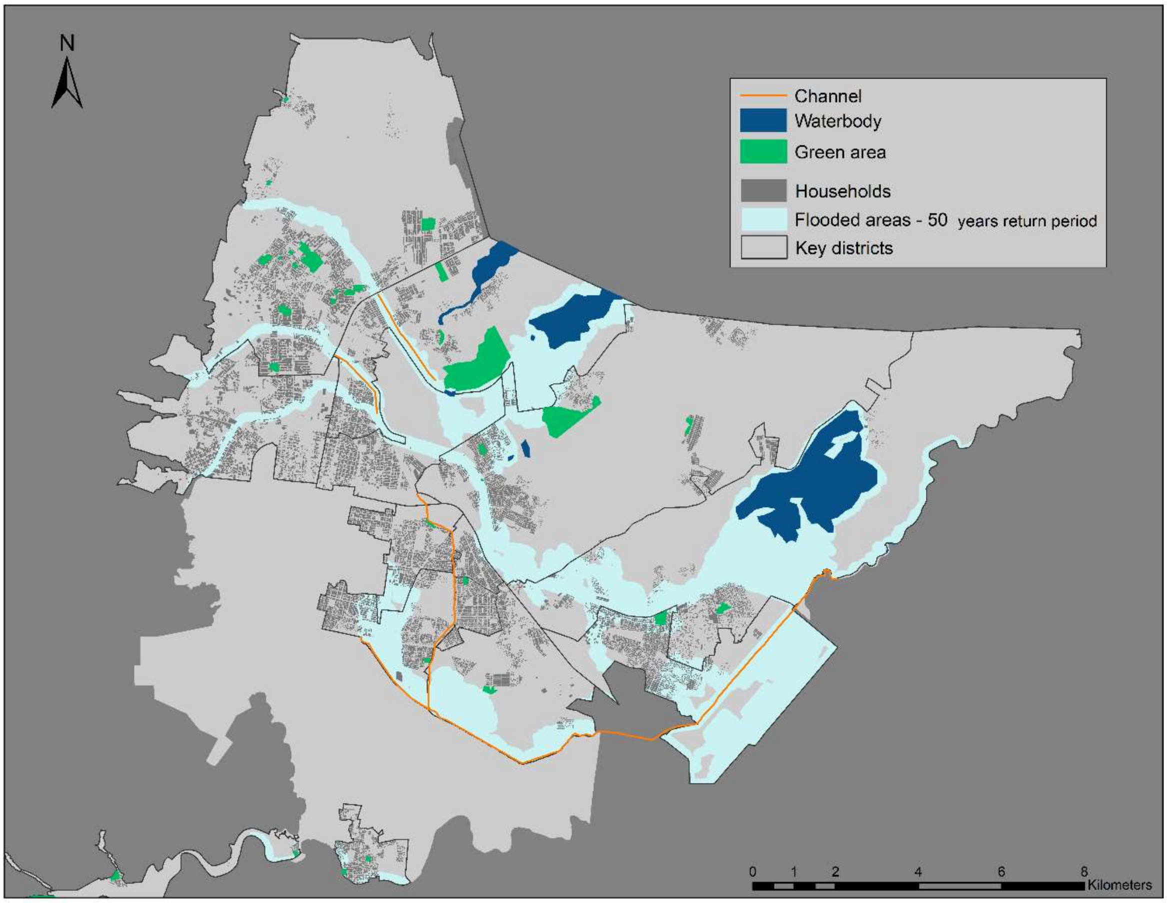

Figure 14 Drainage channels (orange), environmental assets (green), and water bodies (blue). Source: Authors' own compilation.

Since rivers and canals change theirs shape and width over their course, the average width based on the employed flood model, described in Chapter 2, are being applied for simplification. The value estimates are based on reports from exports of the Municipality on prices per m^2 for clearing and reconstruction of affected areas, which is about 201.6 USD/m^2. For the four considered rivers/ canals this translates to the following Table 11.

Table 11 Drainage value estimates

	Length (m)	Average width (m)	Total area (m^2)	Total value (USD)
Rio Bermejo	1 839	25	45 968	9 267 062
Rio Blanco	2 491	30	74 738	15 067 079
Canal Chotepe	15 113	10	151 126	30 466 943
Canal Sauce	5 891	10	58 907	11 875 627
Total	25 333		330 738	66 676 712

3.10 Environmental Assets

Through increased volumes and flow velocity river banks are being damaged and debris and pollution is being swept from e.g. streets and nearby industrial areas into the riverbed. Based on the Ecosystem Services Valuation Database (ESVD)[24,25] which considers as a follow up to "The Economics of Ecosystems and Biodiversity" (TEEB) database a wide range of ecosystem services for different biomes rivers and lakes, water bodies were valued at 108 361 USD/year per km (or hectare in the case of lakes) taking into account the different ecosystem services they provide.

For green spaces and forest areas within the research area, value estimates (5 383 USD/year/ha) are being drawn from the ESVD as well, considering both the material value as well as the value added through ecosystem services such as air quality and climate regulation. In this study only the value for one year is being applied for simplification; Table 12 summarises the value estimates; Figure 14 above displays the identified environmental assets (green) and water bodies (blue).

Table 12 Environmental assets value estimates

	USD/ha	Total ha	Total USD
Lakes/ Water bodies	108 361	690	74 775 592
Forests/ Green spaces	5 383	401	2 156 648
Total		1 091	76 932 240

3.11 Heritage Sites

Sites of cultural heritage are drawn, such as all buildings, based on their location in the cadastre. However, value estimates are not based on the cadastre but again on the advice and internal estimates provided by experts of the Municipality during bilateral discussions to refine estimates (about 483.87 USD/m^2). In total the 41 relevant heritage sites were identified, as presented in Figure 15, taking up a space of 40 067.22 m^2 and with a mean size of about 977.45 m^2. The largest heritage site occupies more than 10 500 m^2 and the smallest only 122 m^2. Table 13 summarises the value estimates for heritage sites.

Table 13 Heritage sites value estimates

	Number	Total area	USD/m^2	Total value USD
Heritage Sites	41	40 067	487	19 387 328

[24] R. De Groot, Brander, L., Solomonides, S. (2020). *Ecosystem Services Valuation Database (ESVD). Update of global ecosystem service valuation data*. FSD report No 2020-06 Wageningen, The Netherlands (58 pp).

[25] R. de Groot, Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L., ten Brink, P., van Beukering, P. (2012). *Global estimates of the value of ecosystems and their services in monetary units*. Ecosystem Services. Volume 1. Issue 1. pp. 50-61. https://doi.org/10.1016/j.ecoser.2012.07.005.

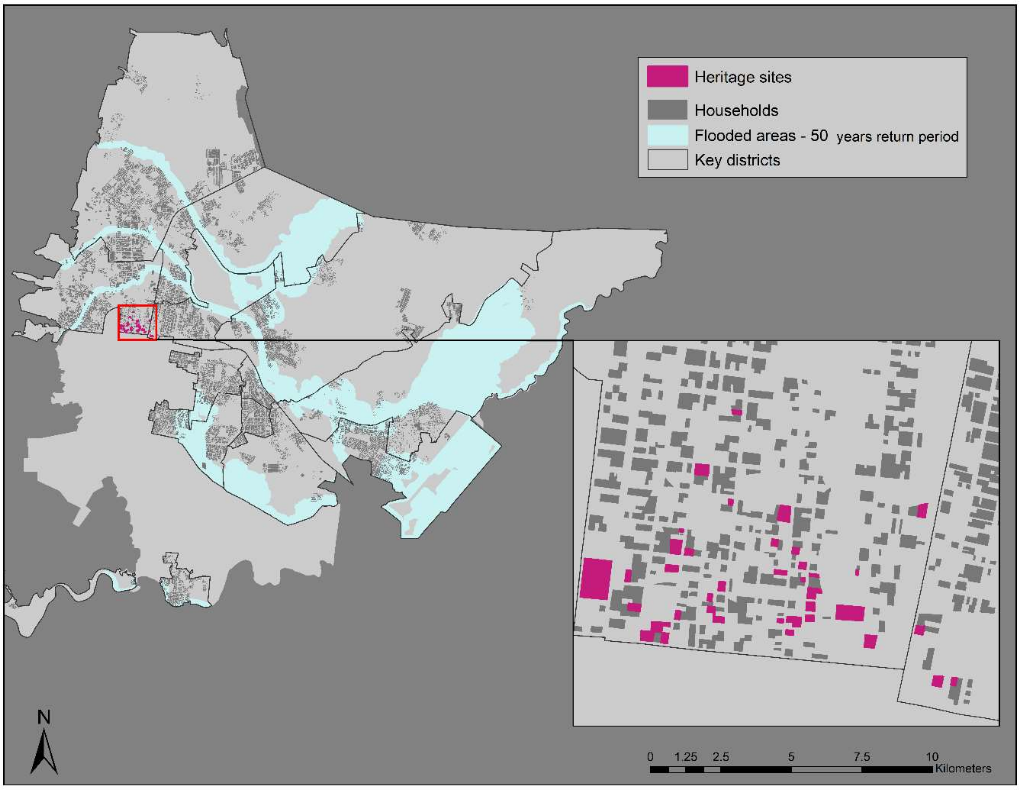

Figure 15 Heritage sites. Source: Authors' own compilation.

3.12 Overview Assets Valuation

To summarise the above sub-chapters on the individual asset categories the following Table 14 provides an overview over the aggregated value per asset category.

Table 14 Compilation of estimated values of assets

Asset Category	Total	Unit	Sample Size
Total Vulnerable Population	30 622	People	30 622
Exposed Population	34 168	People	34 168
Informal Housing (Los Bordos)	40 977 324	USD	6 778 Households
Formal Housing	3 516 200 869	USD	71 615 Households
Roads	951 726 239	USD	8 281 641 m2
Health Facilities	282 771 928	USD	23
Educational Centres	356 456 521	USD	100
Airport – buildings	225 008 495	USD	61 177 m2
Airport - paved areas	49 070 038	USD	426 993 m2
Fire Brigades	1 711 306	USD	4
Electrical Grid	37 449 408	USD	1 187 km
Electrical Substations	1 250 000	USD	2
Drainage	66 676 712	USD	330 738 m2
Lakes and Water bodies	74 775 592	USD	690 ha
Green spaces/ Forest	2 156 648	USD	401 ha
Heritage Sites	19 387 328	USD	41
Total Population	**64 790**	**People**	
Total Asset Value	**5 625 618 408**	**USD**	

4 DAMAGE FUNCTIONS

4.1 Introduction

Potential future damage caused by floods depends on several parameters including: 1) Climatic and socio-economic conditions, which were described in detail within the Data Report, their incorporation into CLIMADA, and their effects on the estimation of damages are explained in Chapter 6. 2) The asset valuation, which is presented in Chapter 3. And 3) Sensitivity to floods, which is commonly assessed using depth-damage curves, also known as damage functions or vulnerability curves, denoting to what degree a certain asset type is being affected at different inundation levels (i.e. the hazard intensity).

Different approaches can be used to design damage curves. One approach uses historical data on both inundation levels and recorded damages, reconstruction cost or depreciated values of the assets. With sufficient data available this approach is very precise within a reference area. Alternatively, it is possible to estimate probable damages based on expert opinions regarding materials, buildings' structures and other characteristics of the respective assets. This method is particularly helpful when no or insufficient historical records are available. Last, one can rely on generic or empirical damage functions and subsequently calibrate them using (household) surveys such as the one performed by DIEM in early 2020.

In any case, an iterative calibration process of the resulting damage functions is necessary to ensure that the damages simulated by CLIMADA reflect historical damages in the region[26].

The following section introduces the damage functions as used in CLIMADA. For the sake of clarity, all figures are displayed in the same format. Even though the ordinate axis reaches up to 120%, the mean damage degree (MDD) cannot exceed 100%. Similarly, damage functions are only shown up to an inundation level of 7m, representing the maximum value in the flood model (see Chapter 2).

[26] Damage functions are one of the most sensitive parameters in CLIMADA. Despite our efforts to approximate them, a calibration of their shape is necessary. The iterative calibration process includes multiple runs of CLIMADA fitting simulated damages with historical events. The parameters linked to the damage functions (shape, threshold etc...) are altered until the overall annual expected damage (AED) simulated offers an acceptable range of the historical AED. The damage functions presented here are the final damage functions.

4.2 Vulnerable People

An S-shaped curve was assumed based on local experts' opinions, the results of the household survey and a literature review[27,28,29]. Two separate damage functions are created. One for the general population of San Pedro Sula (people) and another one for inhabitants of *Los Bordos* (People in *Los Bordos*). Because people living in *Los Bordos* are more vulnerable the same inundation levels inflict damages earlier and they are affected stronger. Therefore, the curve for people in *Los Bordos* displays a MDR with a maximum of 100% (see Figure 16), while a maximum of 80% is assumed for the rest of the population, which is assumed to have a stronger resilience to flood (Figure 17).

Figure 16 Damage function for People in Los Bordos

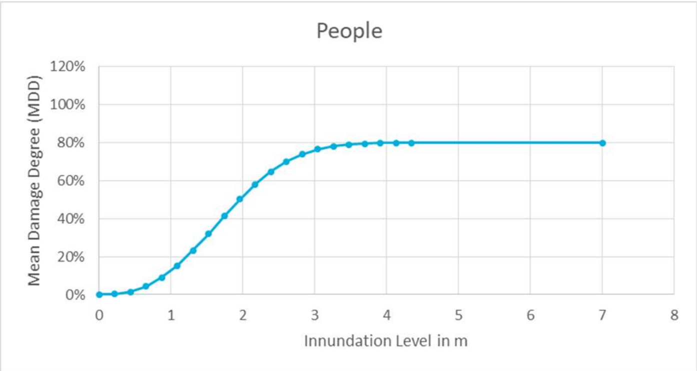

Figure 17 Damage function for People not living in Los Bordos

4.3 Informal Settlements (Housing in Los Bordos)

Informal settlements, i.e. housing in *Los Bordos*, are located within or around the riverbeds. For these assets, an S-shaped curve is recommended[30,31]. With rising waters, damages accumulate

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[27] Jonkman, S. N.; Vrijling, J. K.; Vrouwenvelder, A. C. W. M. (2008): *Methods for the estimation of loss of life due to floods. A literature review and a proposal for a new method*. In Nat Hazards 46 (3), pp. 353-389. DOI: 10.1007/s11069-008-922

[28] Jonkman, S.N.. (2007). *Loss of Life Estimation in Flood Risk Assessment: Theory and Applications*. PhD thesis, Delft University of Technology.

[29] GFA Consulting Group. (2015). Climate Change Adaptation in Urban Areas in Central America. El Salvador. Vulnerability Analysis + ECA Draft Report. Hamburg

[30] See e.g.GFA Consulting Group. (2015). *Climate Change Adaptation in Urban Areas in Central America. El Salvador. Vulnerability Analysis + ECA Draft Report*. Hamburg

[31] K. Zabert et al. (2018*). Development of model for the estimation of direct flood damage including the movable property*. J Flood Risk Management. 11. S527-S540. DOI: 10.1111/jfr3.12255

exponentially before reaching a peak threshold. For informal housing in *Los Bordos*, other than for most buildings, it is assumed that valuables and structures are of poorer quality and will be potentially completely destroyed (maximum MDD = 100%). 80% of MDD is expected already at 2m as presented in Figure 18. This curve was validated using the data obtained through the DIEM (2020) survey covering three historical flood events. Subsequently, the damage functions were adjusted to EM-DAT data in order to produce realistic aggregated values in the context of SPS. These values are presented in detail in Chapter 6.

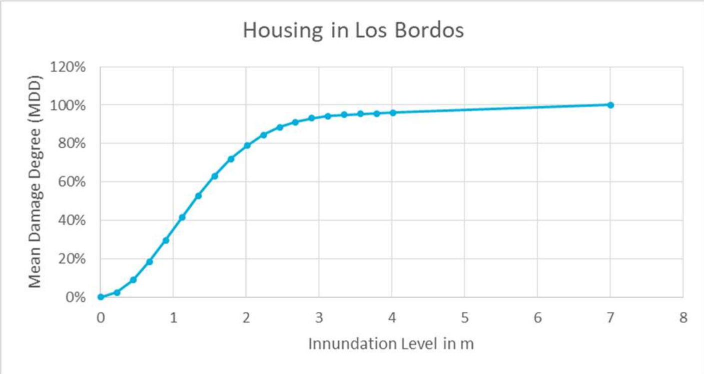


Figure 18 Damage function for Informal Housing in Los Bordos

4.4 Formal Housing

Following a similar approach, the damage function for housing is S-shaped, with a maximum MDD of 40%. Structures are stronger, build quality is higher and some houses have multiple stories[32,33]. Maximum MDD is expected to be reached at 3m of inundation as presented in Figure 19.

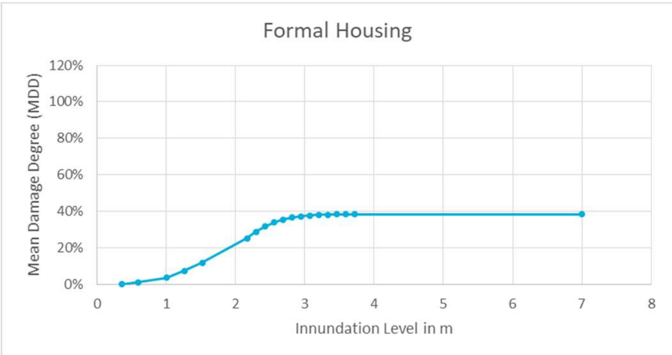


Figure 19 Damage function for Formal Housing

4.5 Road Network

The road network considered in this study is paved with a stronger groundwork. Hence, a maximum degree of damage of just below 50% is assumed, which is reached at a flood depth of 4m. To reproduce

[32] Ibid.

[33] Huizinga, J., Moel, H. de, Szewczyk, W. (2017). *Global flood depth-damage functions. Methodology and the database with guidelines*. EUR 28552 EN. doi: 10.2760/16510

small damages often observed with flood events, 20% of damage occurs with water levels of 1.30m (see Figure 20)[34,35,36].

Figure 20 Damage function for the Road Network

4.6 Public Buildings

The damage curves for the public buildings depend on their specific purpose of the infrastructure. For instance, interior fittings and furniture varies between health centres, schools or fire brigade and are therefore considered in the respective damage functions. In general, damage functions presented here for Educational Facilities, Health Facilities, Airport Buildings, and Fire Brigades are largely based on expert knowledge and desk research in the region[37,38,39].

4.6.1 Educational Facilities

For educational facilities, the damage is expected to rise sharply with increasing water levels. Indeed, furniture, such as tables, chairs, and other traditional school supply are most vulnerable to water rise. Infrastructure is generally more resilient and expected to resist even high level of water. Consequently half of the expected maximum MDD happens at 0.3m whereas the maximum MDD (50%) is reached at 2m (Figure 21).

[34] Huizinga, J., Moel, H. de, Szewczyk, W. (2017). *Global flood depth-damage functions. Methodology and the database with guidelines*. EUR 28552 EN. doi: 10.2760/16510

[35] M. Kok et al. (2005). *Standard Method 2004 Damage and Casualties by Flooding*. Ministerie von Verkeer en Waterstaat. Rijkswaterstaat.

[36] GFA Consulting Group. (2015). *Climate Change Adaptation in Urban Areas in Central America. El Salvador. Vulnerability Analysis + ECA Draft Report*. Hamburg

[37] Huizinga, J., Moel, H. de, Szewczyk, W. (2017). *Global flood depth-damage functions. Methodology and the database with guidelines*. EUR 28552 EN. doi: 10.2760/16510

[38] M. Kok et al. (2005). *Standard Method 2004 Damage and Casualties by Flooding*. Ministerie von Verkeer en Waterstaat. Rijkswaterstaat.

[39] GFA Consulting Group. (2015). *Climate Change Adaptation in Urban Areas in Central America. El Salvador. Vulnerability Analysis + ECA Draft Report*. Hamburg

Figure 21 Damage functions for Educational Facilities

4.6.2 Health Facilities

For health facilities, the increase of damages is slower because most valuables are not stored directly on the ground but are stored higher. The resulting S-shaped curve is displayed in Figure 22. We propose a maximum MDD of 60% for water levels at about 3m, with 40% of damages occurring already at 2m.

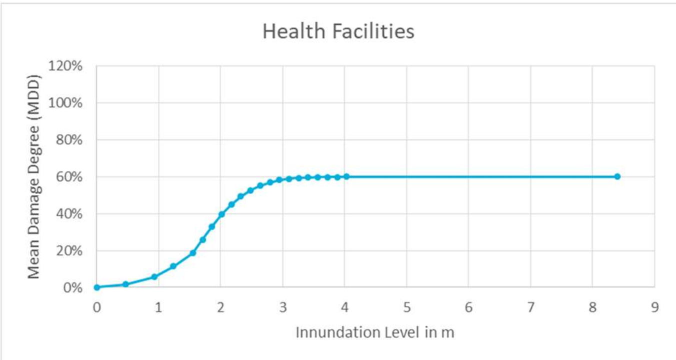


Figure 22 Damage function for Health Facilities

4.6.3 The Ramón Villeda Morales International Airport

The regional airport has been divided in two distinct types of assets i) paved areas (taxi- and runway) and ii) airport buildings. For the paved areas, a linear damage function is applied with a maximum MDD of 90% for 3.5m (Figure 23). The damage function is adapted from Kok et al. (2005). The damage function for other buildings at the airport follows an S-shape similar to the one used for health facilities with a maximum MDD of 95% for 2.5m based on observations of recent damages (Figure 24).

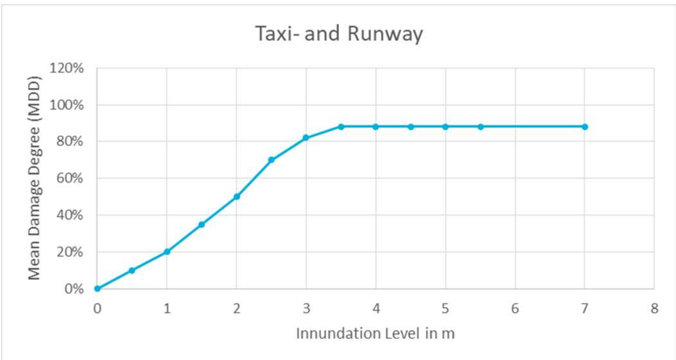


Figure 23 Damage function for paved areas at the Airport (Taxi- and Runway).

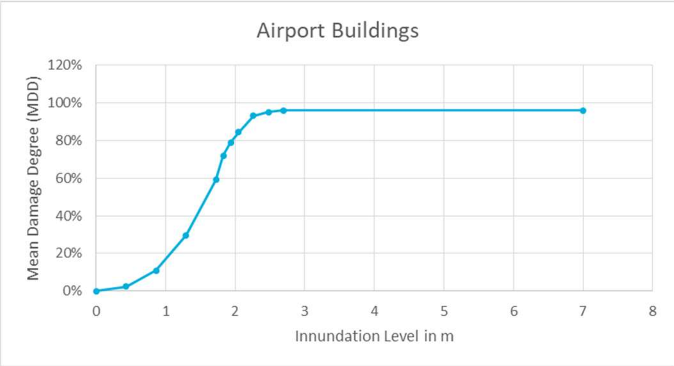


Figure 24 Damage function for Airport Buildings.

4.6.4 Fire Brigades

The damage function for the fire brigades follows an S-shape with a slight increase of damage at lower flood levels, with a maximum MDD of about 50%, see Figure 25.

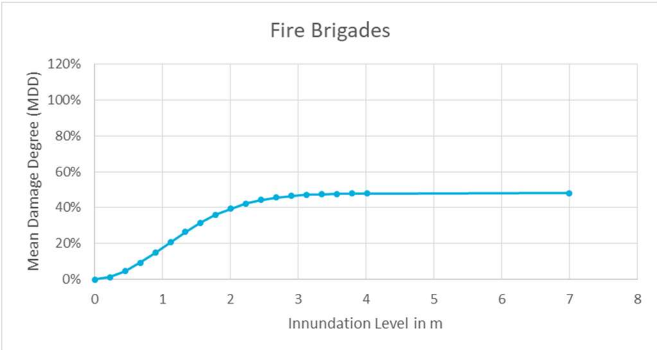


Figure 25 Damage function for Fire Brigades.

4.7 Electrical Infrastructure

For electrical grid, a linear damage curve is assumed[40] to reach its maximum damage degree of 100% at 3m while a mean damage degree of 50% is reached at about 1.5m (see Figure 26). For electrical substations, with most of them being elevated[41], the maximum MDD of 50% is reached at an inundation level of 4m. The MDD plateaus afterwards with stations being submerged (Figure 27).

[40] See e.g. M. Kok et al. (2005). *Standard Method 2004 Damage and Casualties by Flooding*. Ministerie von Verkeer en Waterstaat. Rijkswaterstaat.

[41] See e.g. Federal Emergency Management Agency, Mitigation Division, Department of Homeland Security. *Hazus-MH, Flood Model, Technical Manual*. Washington, D.C. https://www.fema.gov/media-library-data/20130726-1820-25045-8292/hzmh2_1_fl_tm.pdf, retrieved on 08.09.2020

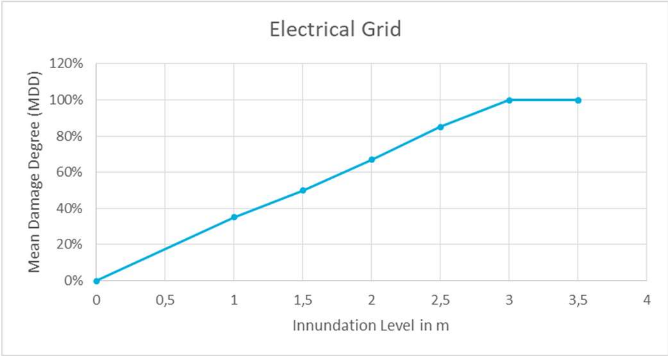


Figure 26 Damage function for the Electrical Grid.

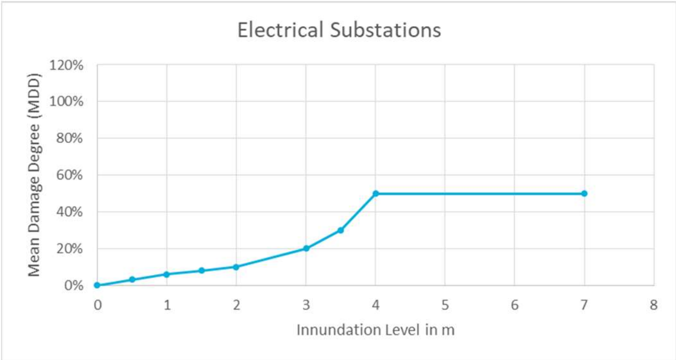


Figure 27 Damage functions for Electrical Substations.

4.8 Drainage Channels

Since the drainage system is limited to some (natural) rivers and canals, which both have the purpose of channelling (flood) waters, a flat damage function has been constructed in line with literature suggesting that little damage should be expected[42]. However, in the light of recent events (Storms Eta and Iota) it has to be assumed that at least some damage is being caused by extreme events. Hence, the damage function displayed in Figure 28 has been constructed. This damage function has the feature of two increasing phases. While initially the MDD is kept at 0% up to 1.5m, water levels that cause no damages to the existing channels, a slight increase toward the first plateau of 10% at water levels between 3m and 4m is achieved before the maximum MDD of 20% is reached at a level of 5m.

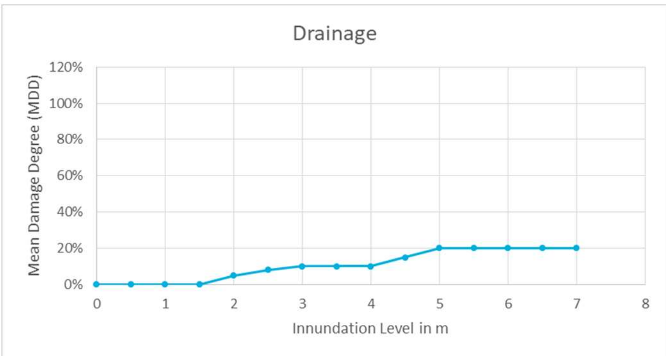


Figure 28 Damage function for the Drainage System.

[42] Ibid.

4.9 Environmental Assets

With regard to green spaces, forest, and parks the approach presented here is adapted after Kok et al. (2005)[43]. The maximum MDD is set at 100% with first a slight, followed by a sharper increase which converges toward the maximum level reached at 4.5m (Figure 29).

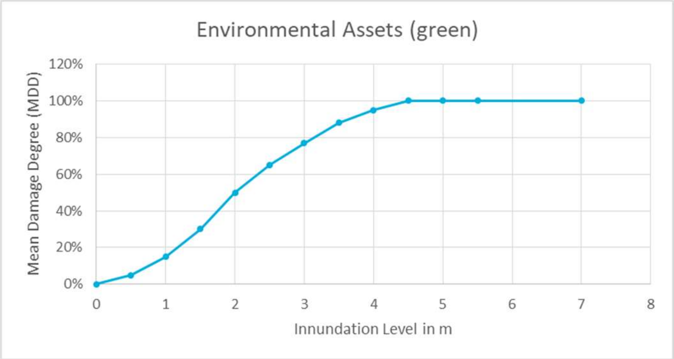


Figure 29 Damage function for green Environmental Assets.

For water bodies different literature sources were consulted with studies suggesting all three, positive, negative and neutral effects for smaller floods[44,45]. Eventually, whether the positive or the negative effects take the upper hand during smaller floods depends on many factors such as seasonal, climatic, and weather conditions prior and after to the flood event or for instance characteristics of the river bed sediments.

Extreme floods, on the other hand, are almost unanimously considered to have no positive effect due to increasing soil erosion, pollutant contamination or organic matter. Based on that the applied damage function is constructed with an initial positive effect (e.g. recharging groundwater and wetlands, creating wildlife habitat, or rejuvenating soil fertility) of small floods with its maximum (5%) at 0.5m flooding up until a level of about 1m before the negative effects outweigh the positive one. From there onwards it follows an S-shape with a maximum MDD of 90% reached at 7m (see Figure 30).

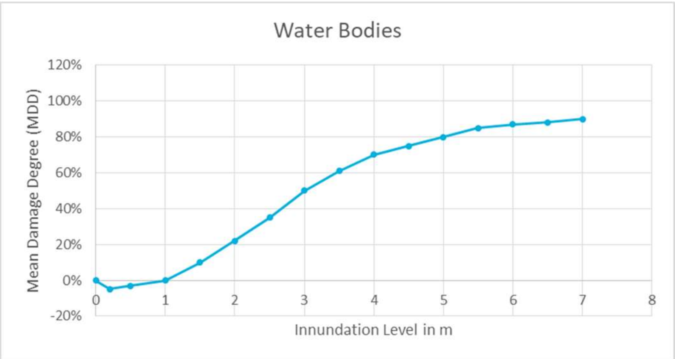


Figure 30 Damage function for Water Bodies.

[43] M. Kok et al. (2005). *Standard Method 2004 Damage and Casualties by Flooding*. Ministerie von Verkeer en Waterstaat. Rijkswaterstaat.

[44] See e.g.: C. J. Talbot et al. (2018). *The impact of flooding on aquatic ecosystem services*. Biogeochemistry 141. 439-461. https://doi.org/10.1007/s10533-018-0449-7

[45] Or see: T. Hrdinka et al. (2012). *Possible impacts of floods and droughts on water quality*. Journal of Hydro-environment Research 6 (2012) 145 - 150

4.10 Heritage Sites

Heritage sites display an S-shaped path with a first increase of MDD at an inundation level of 1m reaching its maximum MDD of 60% at a level of 3m. The shape follows similar buildings related damage functions (Figure 31).

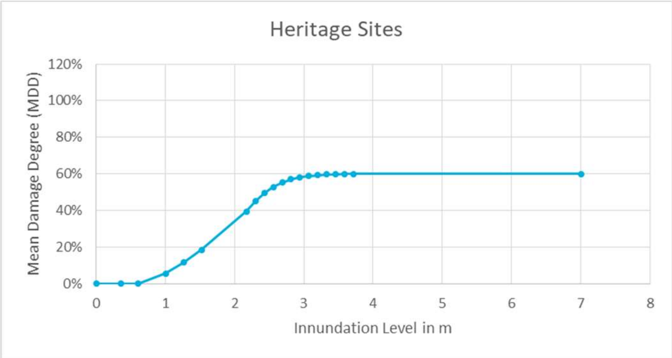


Figure 31 Damage function for Heritage Sites.

4.11 Limitations

Estimating damages in correlation with flood intensities is a difficult exercise asking for a variety of data and information being brought together. While the damage functions developed initially offer a good estimation of potential damages, they have been altered during the calibration runs within CLIMADA (final curves presented here). In addition, their potential in estimating a single asset's damage is limited and they aim at an aggregated representation of the asset category as a whole. By that, they target the *average* asset and should be handled with care if applied in other regions and without calibration.

In general, the field of damage ratios, especially for flood hazard, is subject to discussions on the degree of generalisation and specialisation and the respective components of flood damage functions.[46] The core challenge in constructing damage functions, independent of the considered parameters (e.g. inundation level, flow velocity, duration), is the availability and (public) accessibility of high quality data recorded after similar events which are critical to construct baseline damage functions that can be refined and calibrated in each individual context.

[46] As a good reference on flood damage and its assessment one could consult B. Merz, Kreibich, H., Schwarze, R., and Thieken, A. (2010) Review article. *"Assessment of economic flood damage"*. Nat. Hazards Earth Syst. Sci., 10, 1697–1724, https://doi.org/10.5194/nhess-10-1697-2010

5 ADAPTATION MEASURES

5.1 Introduction

This chapter presents a list of flood adaptation measures identified for the municipality of San Pedro Sula. These measures will serve to reduce the vulnerability of the key assets and population groups selected during the Inception Workshop, by reducing either the number of assets expected to be affected, the intensity of the affectations or in some cases both. The benefit of each measure was linked to the potential averted damage.

The adaptation measures were selected based on a comprehensive literature review, and a consultation process with government officials from San Pedro Sula. In total 47 adaptation measures were initially identified (referred to as “long list”) and reduced to 14 (referred to as “short list”), of which 12 measures were introduced to CLIMADA and later 3 were highlighted as optimal by the modelling platform. These 3 measures will go through a more detailed assessment during the last stage of the ECA study, in which prefeasibility analysis is carried through, see Chapter 9 for details.

Reducing the list of measures from 47 to 14 involved a transparent and participative selection process, including several stakeholder assignments and conducting a Multi-Criteria Analysis. A detailed description of the measures selection procedure can be found in ANNEX 5.

5.2 Flood Adaptation Measures

The 14 flood adaptation measures identified and validated by the Municipality (short list) can be classified as follows: 4 as ‘Grey’ measures, referring to technological and engineering solutions. 5 as ‘Green’ measures, which refer to ecosystem-based (or nature-based) approaches and make use of multiple services provided by natural ecosystems. 2 as ‘Operational’ measures whose purpose and focus are on any type of maintenance/operation that is introduced or improved to a specific area. 2 as ‘Monitoring’ measures, hence including instruments/tools that improve baseline information of existing river and weather conditions and support future predictions of flood events. The final list of measures also includes one ‘Insurance’ solution, which can provide coverage for at least some of the residual risks remaining after the other measures are implemented. Table 15 depicts an overview of our short list, including their total cost and respective type.

Table 15: Overview List of Flood Adaptation Measures for San Pedro Sula.

#	Name of Measure	Type of Measure	Zone	Total Cost (USD)
1	Establishment of flood collectors (Drainage system)	Grey	A, B, C	34 757 657
2	Water collection in existing buildings	Grey	A	563 257
3	Dry Flood-Proofing (housing)	Grey	A, C	6 243 582
4	“El Tablon” Hydropower Dam	Grey	C	279 489 491
5	Ecological restoration of river bank slopes	Green	A, B	834 721
6	Dry Detention Basins	Green	A	17 588 986
7	Reforestation of green spaces in urban areas	Green	A, B, C	8 226 158
8	Green Roofs	Green	A	22 893 988
9	Vegetated swales	Green	A, C	857 802
10	Flood Awareness & Preparedness Campaign	Operational	A, B, C	1 457 199
11	Community based solid waste management	Operational	A, B	1 794 590
12	Parametric Index Insurance*	Insurance	A, B, C	-

Figure 32 shows the different zones where measures have been allocated. Zone A describes a zone where measures have an influence on the flood plain of the basin from *Río Blanco*, typically, measures constructed upstream in the river. Zone B describes a zone that represents the central flood plain from the river basins of *Rio Piedras*, *Rio Bermejo* and *Rio Chotepe*. Zone C represents the flood plain south of the city from Rio Chamelecón.

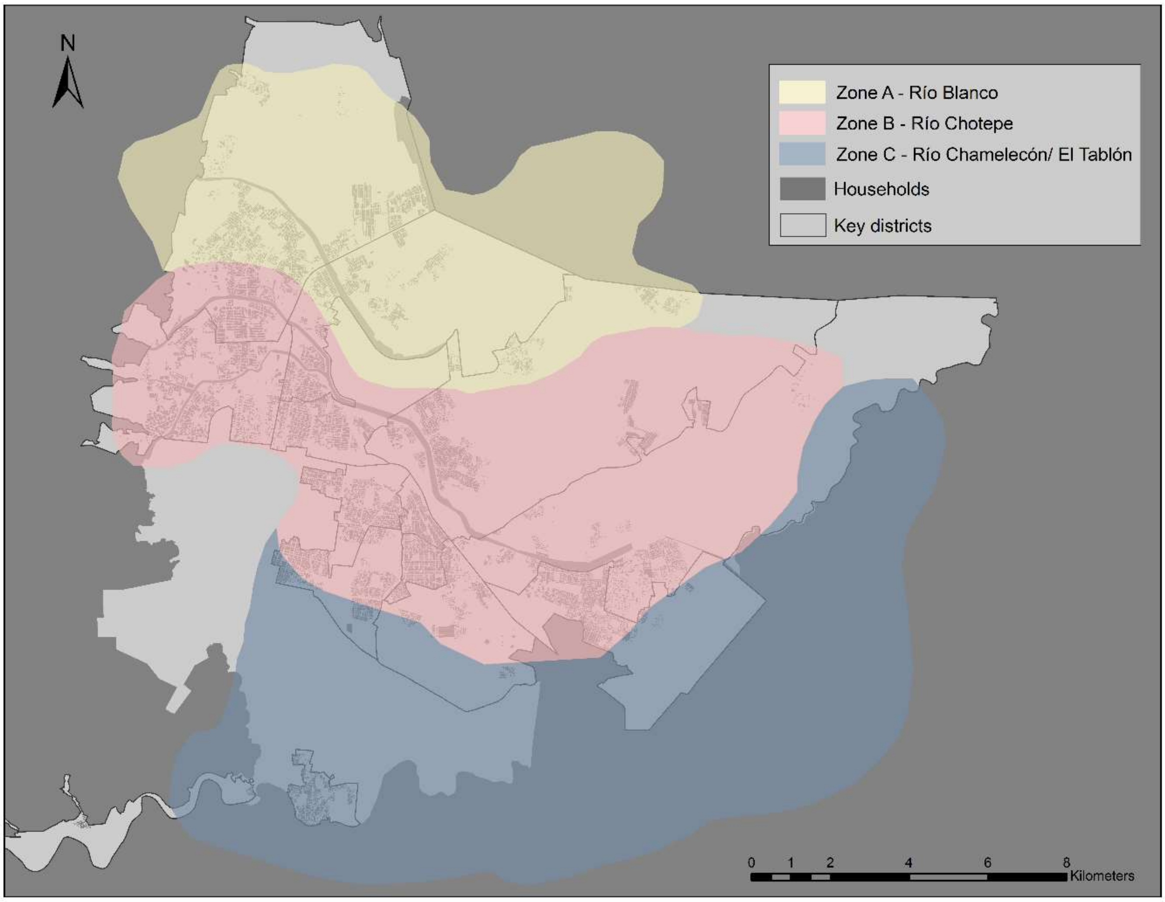


Figure 32: Overview of the zonation: A.) Río Blanco catchment, B.) Río Chotepe, Río Bermejo, Río Piedras and Canal Sauce catchment, C.) Río Chamelecón catchment

The measures are described in brief in the following overview tables (Table 16). Each box provides information about the cost per assigned location (A, B, or C), the implementation time, expected life span, complexity and maintenance intensity. A more precise description of each measure can be found in ANNEX 6.

Table 16: Description of intended flood adaptation measures (14 measures). For each measure the table provides the cost per assigned location (A, B or C), implementation time, expected life span, complexity of the measure (in high, medium, low) and maintenance intensity (in high, medium, low).

1. Establishment of flood collectors (drainage system)

The Municipality's storm water drainage system is crucial to collect high quantities of water, which accumulate in large amounts on the streets and passages. All systems consist of reinforced concrete channels, mainly of trapezoidal shape. This study considers sections of the drainage system that are in planning and design as well as existing systems that are planned to be improved, i.e. refurbished to ensure a full functioning.

New collectors (designed & planned): In Zone A and B flood collectors will be constructed which have been designed and planned with respective lengths of 1 482 meters and 15 602 meters.

Total Cost (USD)	3 742 701 (Zone A), 29 990 926 (Zone B)		
Implementation Time	2 years	Complexity	Medium
Life Span	20 - 30 years	Maintenance	Medium
Impact Reduction	Low (Zone A), High (Zone B)		

Refurbished collectors (existing): In Zone A, B and C, existing collectors will be refurbished with respective lengths of 5 916 meters, 28 430 meters and 1 110 meters.

Total Cost (USD)	246 769 (Zone A), 607 488 (Zone B), 169 771 (Zone C)		
Implementation Time	2 years	Complexity	Medium
Life Span	20 - 30 years	Maintenance	Medium
Impact Reduction	Medium (Zone A), High (Zone B), Low (Zone C)		

Total Cost (New & Refurbished Collectors) per Zone	3 989 471 (Zone A) 30 598 415 (Zone B) 169 771 (Zone C)

2. Water collection in existing buildings

This measure aims to collect rainwater in public and private buildings that have the capacity to accommodate one or more rainwater collection tanks with a specified capacity of 2 500 liters. These collection tanks will be connected to public storm drainage systems or other waterways for discharge. It is intended to introduce water collection tanks to district 1 and 3. Combined, there is a potential of installation for 1 296 buildings.

Total Cost (USD)	563 257 (Zone A)		
Implementation Time	1 year	Complexity	Low
Life Span	20 - 30 years	Maintenance	Low
Impact Reduction	Low		

3. Dry Flood-Proofing (housing)

Dry flood-proofing involves sealing the exterior of a building to prevent the entry of flood waters. It reduces the potential for flood damage by reducing the probability that the building interior will be inundated. A combination of Three dry flood-proofing measures will be implemented per house: (1) backwater valve (blocker), (2) waterproof coating of walls, (3) installed flood shields over doors, windows and openings. It is intended to adapt houses with dry flood proofing in district 1 and 3 (Zone A) and 18 (Zone C), consisting of 1 424 buildings in total with an average size of 82 m².

Total Cost (USD)	4 543 685 (Zone A), 1 699 896 (Zone C)		
Implementation Time	1 year	Complexity	High
Life Span	>30 years	Maintenance	Medium
Impact Reduction	High (for 1 meter flood depth)		

4. "El Tablon" Hydropower Dam

The "El Tablón" Multipurpose Dam project aims to protect of the Sula Valley against floods caused by the Chamelecón River as well as the generation of electric energy based on renewable resources, with a targeted capacity of 20 MW and yearly energy generation of 99 GWh. In addition, the dam will support planned project components for drinking water supply in the Sula Valley (capacity of 4 m3/sec) and irrigated agriculture in the Naco Valley, covering 3 000 ha.

The dam will be constructed in the Chamelecón River, 1.9 km south of the village El Tablón. The dam will be approximately 20 km southwest of San Pedro Sula and 2.5 km downstream from the confluence with the La Mina ravine, in the department of Santa Bárbara, municipalities of Quimistán and Petoa. The area of the dam reservoir includes jurisdictions of the municipalities of Quimistan, Petoa and San Marcos.

Total Cost (USD)	279 489 491 (Zone C)		
Implementation Time	7 years	Complexity	High
Life Span	>30 years	Maintenance	High
Impact Reduction	High		

5. Ecological restoration of river bank slopes

This measure introduces re- and/or afforestation practices in undeveloped areas close to the riverbanks and slopes to replace grass or fallow land with dispersed vegetation. The purpose is to reduce the run-off volumes, overland flow and potential erosion of slopes. It is planned to reforest river bank slope along the Rio Blanco (Zone A) and Chotepe (Zone B) with native tree species including Pine (Pinus spp), Cedar (Cedrella odorata) and Mahogany (Swietenia macrophylla). In total an area of 191 hectares is targeted for re- and afforestation.

Total Cost (USD)	411 965 (Zone A), 422 755 (Zone B)		
Implementation Time	1 year	Complexity	Low
Life Span	>30 years	Maintenance	Low
Impact Reduction	Medium (Zone A), Low (Zone B)		

6. Dry Detention Basins

Detention basins are dry vegetated depressions in the ground. They are usually designed to provide short term storage of water and remain dry outside of storm periods. Detention basins can retain flood events, reducing peak flows and limiting the risk of flooding. It is planned to establish 10 detention basins in the municipalities area, covering district 1, 3, and 4 which is in the catchment of Rio Blanco (Zone A). Each basin will be designed with a depth of 1 meter to allow the multifunctional purpose of the basins.

Total Cost (USD)	17 588 986 (Zone A)		
Implementation Time	1 year	Complexity	Low
Life Span	> 30 years	Maintenance	Low
Impact Reduction	Medium		

7. Improvement & Reforestation of green spaces in urban areas

Urban green spaces have been identified in the municipality. These public spaces such as, city parks and local parks will be further refined to host native tree species. The long-term goal is to create an urban forest heritage, in which every tree element that is located in public areas will be considered as heritage, so its protection, care and maintenance is important for GHG mitigation and the reduction of the effects of climate change, among other benefits to the municipality. This measure considers reforestation with native species in urban green spaces including Pine (Pinus spp), Cedar (Cedrella odorata) and Mahogany (Swietenia macrophylla). In total, 37 green spaces have been identified with an area covering 361 ha and a suitable planting area of 108 ha, consisting ca. 17 000 trees.

Total Cost (USD)	3 462 444 (Zone A), 1 581 328 (Zone B), 3 182 387 (Zone C)		
Implementation Time	1 year	Complexity	Low
Life Span	> 30 years	Maintenance	Medium
Impact Reduction	Medium (Zone A), Low (Zone B), Low (Zone C)		

8. Green Roofs

Green roofs consist of a growing material placed over a waterproofing membrane on a relatively flat roof. Green roofs not only provide an attractive roofing option but also use evapotranspiration to reduce runoff volume, and provides some detention storage. Green roofs may reduce some pollutants from the rainwater as well, they usually are significant sources of phosphorus due to leaching from the growing media. It is intended to establish green roofs in district 1 and 3, in Zone A (Rio Blanco catchment). There is a potential to introduce 1 269 green roofs, with an average rooftop size of ca. 80 m².

Total Cost (USD)	22 893 988 (Zone A)		
Implementation Time	1 - 3 years	Complexity	Medium
Life Span	> 30 years	Maintenance	Low
Impact Reduction	Low		

9. Vegetated swales

Vegetated swales are frequently used to convey runoff and disconnect impervious areas. A vegetated swale (or bio swale, dry swale) is a broad, shallow, trapezoidal or parabolic channel, densely planted with a variety of trees, shrubs, and grasses. It is designed to attenuate and in some cases infiltrate runoff volume from adjacent impervious surfaces, allowing some pollutants to settle out in the process. This measure proposes the establishment of grass swales of parabolic form to reduce runoff from roadways and/or sidewalks by allowing water to infiltrate. It is planned to establish swales of 2 meters depth and 3 meters width, representing 6 m³ per meter. In total, a length of ca. 140 km is planned throughout the municipality (Zone A & B).

Total Cost (USD)	576 886 (Zone A), 280 917 (Zone B)		
Implementation Time	1 - 2 years	Complexity	Low
Life Span	20 - 30 years	Maintenance	Low
Impact Reduction	Low (Zone A), Low (Zone C)		

10. Flood Awareness & Preparedness Campaign (Impact on persons)

In San Pedro Sula, the flood awareness and preparedness campaign will focus on the most vulnerable group exposed to flood. For this reason, it is intended to strengthen campaign efforts on households living in the “Los Bordos” areas along the urban riverbanks. In total, 6 778 households have been identified. It is intended to enrol every 8 years a flood awareness and preparedness program for the most vulnerable people along the river banks and risk flood prone areas. These campaigns are carried out by municipal agencies in collaboration with respective community associations.

Total Cost (USD)	1 457 199 (Zone A, B, and C)		
Implementation Time	8 years	Complexity	Medium
Life Span	1 year	Maintenance	Low
Impact Reduction	High		

11. Community based solid waste management

Solid waste collections schemes should be organized and scheduled among the communities in the “Los Bordos” areas. Primary goal is to remove accumulating trash within the riverbeds and among the slopes. Attention is given to areas with a high risk of trash accumulation, such as bridges or street culverts. These areas must remain garbage free on annual basis. Such a community waste management and collection scheme for watercourses will also reduce the vulnerability people who live in the immediate proximity of rivers. Such a program will raise social awareness for solid waste management and its relation to urban flood risk. These activities will take place in close liaison with local authorities, social service departments and existing community leadership structures.

Total Cost (USD)	1 794 590 (Zone A, B)		
Implementation Time	1 year	Complexity	Low
Life Span	20 years	Maintenance	Medium
Impact Reduction	Medium		

12. Parametric Index Insurance

Index-based flood insurance is an innovative approach to developing effective pay-out schemes for low-income, flood-prone communities. Index insurance schemes make use of modelling and satellite imagery with other data to predetermine flood thresholds, which could trigger rapid compensation pay-outs. Effective end-to-end solutions will be developed in collaboration with a range of organizations and experts from central and state government bodies, private insurance firms, community-based organizations (CBOs) and nongovernmental organizations (NGOs). Index can be developed for people, housing and road network. For housing and transport we propose an attachment of 0,5m for a cover up to 4,5m, with a pay-out varying per asset (needs to be calibrated).

Insurance Premium (USD)	1Mio/year (Housing), 760K/year (transport), 1.23Mio/year(Persons)		
Implementation Time	1 year	Complexity	medium
Life Span	renewable	Maintenance	low

6 RESULTS

6.1 Introduction

This section presents the results from CLIMADA in three sections as follows: i) the annual expected damage for different scenarios, ii) a cost-benefit analysis of selected measures for inundation, landslides and wind and iii) a comparison of measures according to their mitigation effect in the municipality of SPS.

In the previous chapters, asset values and population estimation have been presented and discussed thoroughly. Further, different climate and socio-economic scenarios have been discussed and introduced in the flood model. Last, a list of measures, specific to the study region and dedicated to mitigation of inundation risk have been designed and parameterized into CLIMADA. This data was processed by CLIMADA against the inundation hazard information described in Chapter 2.

In the ECA Methodology, the benefit of a given adaptation measure is estimated as the expected damage in the future that can be averted by its implementation. Because all measures are therefore allocated a monetary basis, results are comparable, and the measure efficiency (in terms of impact or investment) can be quantified. In doing so, the ECA framework identifies a set of “best” measures that is later considered for a pre-feasibility study prior to investment, se Chapter 9.

6.2 Annual Expected Damage

The annual expected damage (AED) is an estimation of the average foreseeable affectations on assets and people per year, in this case related to floods. This AED can be measured in percentage or absolute values, and incorporates climate change and socio-economic scenarios. Figure 33 shows annual expected damage in the Municipality of San Pedro Sula for assets in USD (*a and b*) and for persons (*c and d*). The first bar (today) in yellow represent the actual AED. The second bar represents the AED due to economic development (for assets) and to population growth (for persons). The light red bar represents the additional AED due to climate change in San Pedro Sula. Last, the dark red bar represents the total aggregated expected damage in 2042, when economic (or population) growth plus climate change are considered.

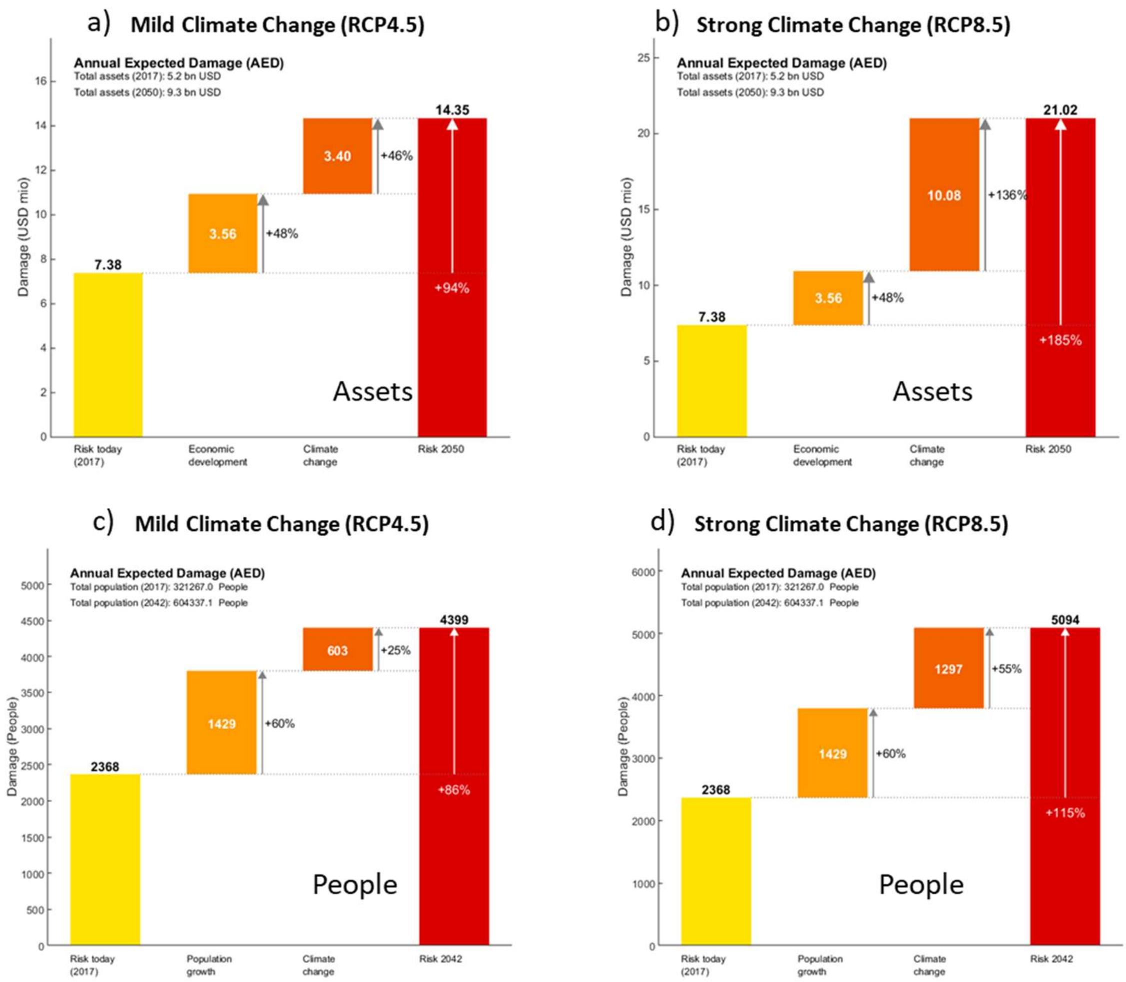


Figure 33 Annual expected damage (AED) in San Pedro Sula for Assets (a, b in USD) and people (c, d in people)

The AED for assets and persons are summarized in Table 17. Results are presented for all scenarios separately and aggregated with today's expected damage. Today is set in 2017 in alignment with the Master Plan for Municipal Development (PMDM) from San Pedro Sula. The total expected damage for assets of USD 7.4m (2017) is projected to rise a 48% due to economic growth[47] and a 46% due to climate change (136% on the extreme climate scenario). A total of USD 14m (USD 21m for extreme climate change scenario) are simulated for the time horizon 2042. The increase in AED in 2042 represents a raise of more than 94% in San Pedro Sula, due both to economic growth (assets will be more valuable) and climate change (hazard will be more frequent and more intense).

Regarding people, more than 2 300 people are expected to be affected by inundation annually in 2017. Despite a relatively low rate of annual population growth is projected for the region, a cumulative increase of 60% is expected by 2042. More intensive climate will affect also increase the number of persons with around 25% more people affected on a moderate climate change scenario and 55% more

[47] For economic growth and the discount rate an average annual rate of 2.24% and 3.3% are applied respectively as described in the preceding data report (Rojas, A, Behre, E, Daou, D, Waldschmidt, F, Sebesvari, Z, Kreft, S, Souvignet, M, (2020), Base Data Report – Honduras –Urban Flood Risk. Report 02. Bonn. UNU-EHS.). For the reader's convenience the details of the economic scenario can again be found in the ANNEX 7.

with extreme climate. A total annual of 4 400 (5 000 for extreme climate) people are expected to be affected in 2042.

Table 17 Summary of annual expected damages in the municipality of San Pedro Sula for different scenarios

ID	Asset Categories	Units	Total Value	AED Today		AED Economic Growth		AED Moderate Climate Change		AED Extreme Climate Change	
101	Population (excl. Los Bordos)	People	293582	2167	*0,74%*	3531	*1,20%*	4098	*1,40%*	4756	*1,62%*
102	Population in Los Bordos	People	27685	201	*0,73%*	266	*0,96%*	302	*1,09%*	338	*1,22%*
201	Housing	USD	3516200870	2603990	*0,07%*	3651220	*0,10%*	5288172	*0,15%*	9511550	*0,27%*
202	Housing in Los Bordos	USD	40977324	1546876	*3,77%*	1584999	*3,87%*	1669661	*4,07%*	1756282	*4,29%*
301	Road Network	USD	40977324	1788828	*4,37%*	2640048	*6,44%*	3235283	*7,90%*	4203732	*10,26 %*
401	Electrical Grid	USD	37449408	83350	*0,22%*	111617	*0,30%*	142948	*0,38%*	213167	*0,57%*
402	Electrical Substations	USD	1250000	-	*0,00%*	-	*0,00%*	-	*0,00%*	-	*0,00%*
501	Health Facilities	USD	282771928	-	*0,00%*	-	*0,00%*	55805	*0,02%*	305234	*0,11%*
502	Educational Facilities	USD	356456521	-	*0,00%*	-	*0,00%*	-	*0,00%*	-	*0,00%*
503	Fire Brigades	USD	1711306	-	*0,00%*	-	*0,00%*	-	*0,00%*	522	*0,03%*
601	Heritage Sites	USD	19387328	-	*0,00%*	-	*0,00%*	-	*0,00%*	-	*0,00%*
701	Drainage	USD	66676712	443287	*0,66%*	1028770	*1,54%*	1144942	*1,72%*	1256757	*1,88%*
801	Airport, Taxiway and Runway	USD	49070038	144002	*0,29%*	318686	*0,65%*	454837	*0,93%*	537549	*1,10%*
802	Airport, Buildings	USD	225008	2477	*1,10%*	3744	*1,66%*	6636	*2,95%*	10369	*4,61%*
901	Environmental Assets, Green (Forest, Green Spaces)	USD	2156648	1456	*0,07%*	2124	*0,10%*	2471	*0,11%*	2966	*0,14%*
902	Environmental Assets, Water Ecosystems	USD	74775592	522598	*0,70%*	1230859	*1,65%*	1686517	*2,26%*	2191809	*2,93%*
All Assets		USD	4 490 086 007	7 382 177	*0,18%*	10 942 803	*0,26%*	14344315	*0,32%*	21 016 569	*0,47%*
Persons		People	321267	2368	*0,74%*	3797	*1,18%*	4399	*1,37%*	5094	*1,59%*

Figure 34 highlights the zoning used to determine the set measures to be evaluated. **Zone A** focuses on the flood plain of the basin from *Río Blanco*, typically, measures constructed upstream in the river. **Zone B** encompasses the flood plain from the river basins of *Rio Piedras*, *Rio Bermejo* and *Rio Chotepe*. And **Zone C** represents the flood plain south of the city from Rio Chamelecón. When no zones are specified the Municipality is considered equally impacted. Defining such zones, allows simulating how clusters of assets might or might not be affected by certain measures, and therefore offers a greater level of analysis. Nevertheless, these zones might change during project implementation, due to a higher level of details needed for the exact planning of each measure.

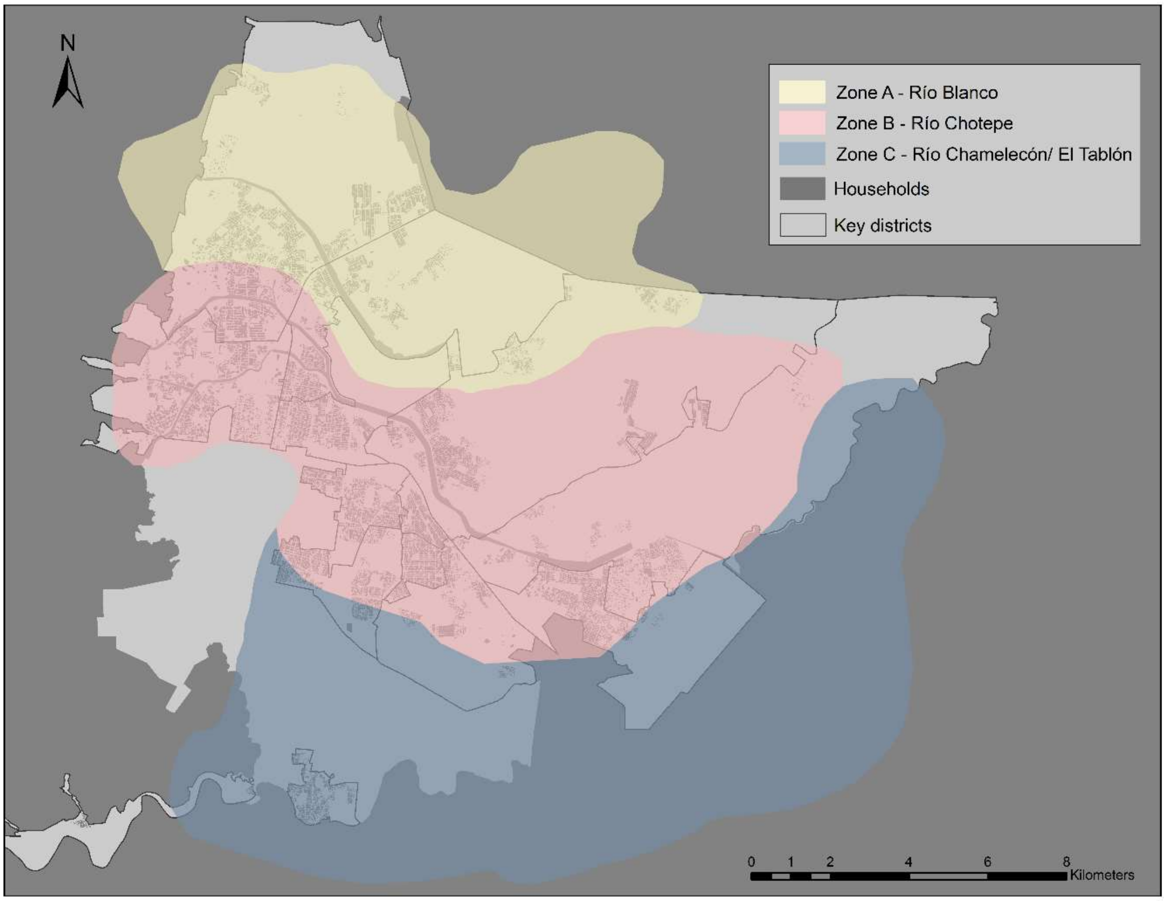


Figure 34 Zones for measures implementation in San Pedro Sula

In order to validate these results against existing events, the annual expected damage (AED) for the Municipality of San Pedro Sula was compared to damage from previous large events. Information about historical events can be found in the open-source EM-DAT data base[48]. Table 18 offers an overview of the last 40 years on record for flood and storm (heavy rain) events in Honduras. Although EM-DAT is an internationally recognized compilation of disaster damages, some local sources propose different figures[49] for overall damages for certain events, which were included in our database.

Table 18 Flood and storm events in Honduras from the EM-DAT international disaster database

Dis No	Year	Disaster Type	Event Name	Total Affected (people)	Total Damages (USD m)
1979-0098-HND	1979	Flood		40 000	13
1990-0115-HND	1990	Flood		48 000	100
1993-0073-HND	1993	Flood		67 447	58

48 http://www.emdat.be/country_profile/index.html

49 *For Mitch, the ECFAC estimated the overall cost for reconstruction at $2.5 billion, which was estimated to take four years.* Description of the Damage (1999). Honduras: Assessment of the damage caused by hurricane Mitch, 1998. Implications for economic and social development and for the environment (Report). Economic Commission for Latin America and the Caribbean. April 1999*. Retrieved 2013-06-07*.

1993-0084-HND	1993	Flood		15 000	57
1995-0186-HND	1995	Flood		25 000	4
1996-0265-HND	1996	Flood		75 000	31
1999-0324-HND	1999	Flood		503 001	2
2002-0329-HND	2002	Flood		969	100
2003-0661-HND	2003	Flood		3 000	20
2006-0338-HND	2006	Flood		1 500	8
2014-0447-HND	2014	Flood		3 000	1
1982-0061-HND	1982	Storm	Alleta	20 000	101
1996-0172-HND	1996	Storm	Cesar and Douglas	-	1
1996-0502-HND	1996	Storm	Marcos	-	1
1998-0345-HND	1998	Storm	Mitch	2 112 000	2 500
2001-0603-HND	2001	Storm	Michelle	86 321	5
2005-0640-HND	2005	Storm	Gamma	90 000	16
2005-0567-HND	2005	Storm	Stan	2 869	100
2007-0439-HND	2007	Storm	Felix	19 500	7
2010-0211-HND	2010	Storm	Hurricane Agatha	24 675	90
2020-0474-HND	2020	Storm	Hurricane 'Eta'	1 712 493	-
2020-0495-HND	2020	Storm	Hurricane 'Iota'	3 000 000	-

Source: EM-DAT, The International Disaster Database (2020)

Table 19 summarizes historical events over the last decades in Honduras. Only flood and storm (heavy rain) will be considered in our analysis. As we know that heavy rain leads to flash floods in the region, we will consider storms as well. Hence, damages due to flood over the last 41 years averages USD 393m, whereas damage due to flood and storm together was USD 3.2 billion. With the metropolitan area of San Pedro Sula accounting for more than two third of the GDP of Honduras, mainly because of the concentration of wealth in economic capital, we assume that damages in the Municipality are proportionally distributed with regards to the national historical damages. Population ratio of SPS accounts for 15% (1.4m) of the total population in Honduras, resulting in 2 133 people affected per year over the last 41 year, in strong agreement with CLIMADA.

Table 19 Annual damage calculation for Honduras and SPS metropolitan area

Catastrophe type	Total damage per catastrophe type (USD m/People)		
	Accumulated Damage (41 years)	AED Honduras	San Pedro Sula
Flood (USD m)	393	10	7
Flood (People Affected)	781 917	14 217	2 133
Storm (USD m)	4 113	69	46
Flood + Storm (USD m)	4 506	79	52
Flood + Storm (no Mitch)	713	18	12

The Sula Valley, as described before, is one of the area most at risk for flood damage. Consequently, the historical annual damage in the region should be close to USD 7m for flood. As we have seen previously, the AED as calculated by CLIMADA in San Pedro Sula is USD 7.5m, underlining therefore the robustness of CLIMADA's simulation in the region. Nevertheless, not all assets are captured in our study, and certain assets are captured that are not normally considered in damage calculation (such as environmental assets). The AED today is therefore larger than historical damage in the records available. The model was not calibrated for storm and flood, which return far greater historical damage values (USD 52m) due to the large damages registered for Mitch. Calculating expected damages without Mitch, which can be considered a strong outlier in just 41 years of historical record, returns an expected annual value of USD 12m for flood and storm events in the Municipality. Notwithstanding, Eta and Iota hurricanes have shown that large and rare events, statistically happening every 100 or 150 years might happen more often and in a short amount of time after another.

6.3 Discussion on Uncertainties

In this section we will discuss the uncertainties associated with the simulations done in this chapter. In a modeling exercise uncertainties are inevitable and should be qualified whenever possible. Figure 35 displays uncertainties associated with each component of the ECA modeling chain.

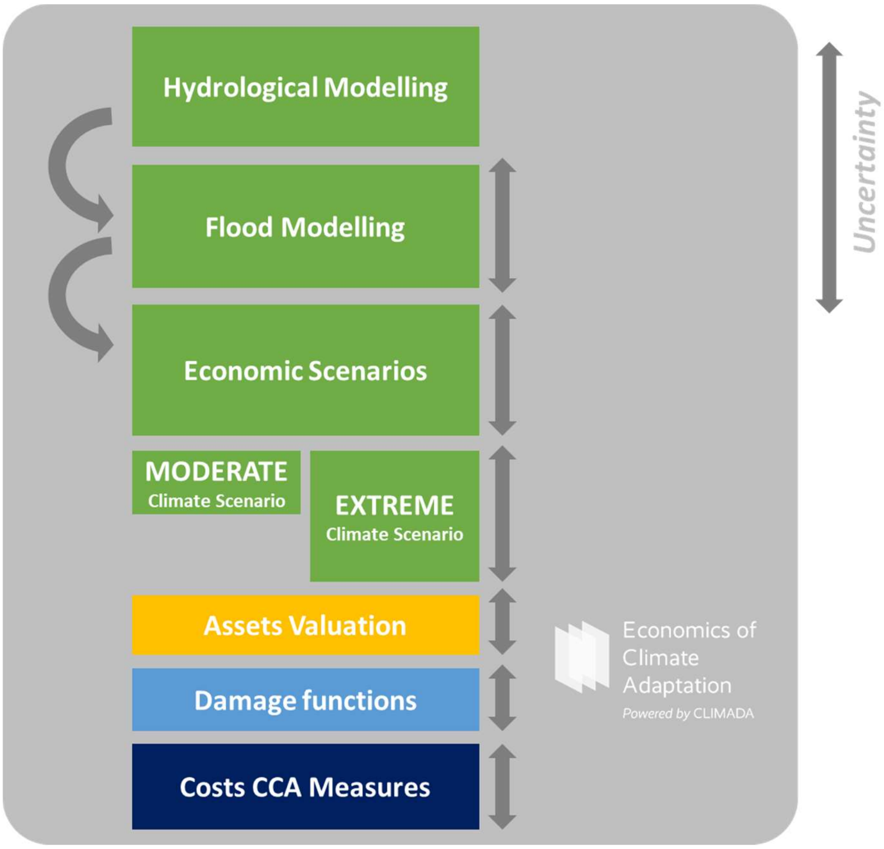


Figure 35 Uncertainty cascade for the CLIMADA modeling chain

The four components are displayed in different colors in order to ease identification of the main sources of uncertainties. Within the component "modeling hazards", disparities exist in how large an uncertainty is between the different models. For inundations, the model uncertainty is dependent on several sources. The first one is the quality of existing rainfall and streamflow observations. The second source concerns the modeling parameters that should be used for hydrologic and hydraulic modeling. These parameters are not always physically based and therefore introduce uncertainty in the modeling cascade. Nevertheless, trough validation by existing observation, there is high confidence in the outputs of the inundation model.

An important source of uncertainty in the ECA methodology is introduced by economic and climate scenarios. Indeed, producing scenarios always introduce uncertainty in a modeling exercise. The economic and population growth scenarios, although based on actual observations, are simple and do not reflect possible fluctuations. Nevertheless, they provide a good estimation of a mean trend and should be treated as such. Climate scenarios are more challenging to evaluate. Although the scenarios used a based on validated scientific data and models, not all climate scenarios agree in their conclusions. In addition, climate models are seldom calibrated for a certain region and especially precipitation simulations are sensitive to scale. Last, there is usually less confidence in extreme scenarios than in moderate scenarios, the latter being often the results of a consensus among different models.

Asset valuation enjoys on the contrary more confidence and introduces less uncertainties in the modelling chain. Indeed, even if assets do not represent the total value in SPS, there is a high confidence – validated by ground field review – that values assigned to assets are representative of reality.

Further, damage functions are the most sensitive parameter in the ECA methodology. Damage function can be determined by mathematic formula or using expert knowledge. In our case, we have tried to reduce uncertainty in using both approaches. Nevertheless, as damage function cannot be validated we assume a quantitative bias introduced by this component.

The quantification, valuation and parameterization of adaptation measures is a challenging exercise. The location and exact size of an engineering project might influence greatly the cost and benefit calculated. In this study, costs, maintenance costs and parameterization was done in close cooperation with local and international experts in order to achieve a reduced uncertainty related to measures. Nevertheless, unless using time-consuming modeling and engineering tools, the exact estimation of measures introduced in CLIMADA is difficult. We assume therefore a moderate confidence concerning the costs and impact of measures presented in this report.

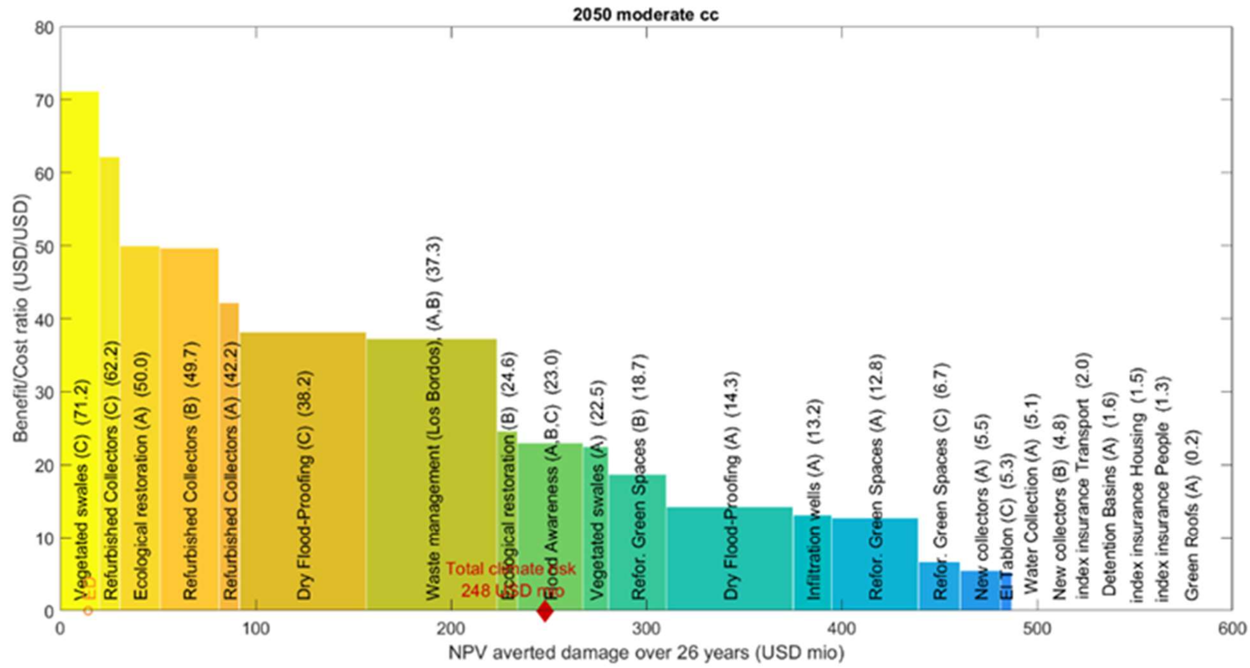
6.4 Cost-Benefit Analysis

In this section the existing relationship between costs (investment and maintenance) and net averted damage of a given measure is analyzed. As stated before the ECA framework estimates the benefit of adaptation measures based on their net averted damage.

First, an adaptation cost curve plots benefit/cost ratio (axis Y) against aggregated averted damages (axis X) for each measures. The value 1 represents the threshold for the benefit/cost ratio, or in other words, values above it are cost efficient while values below it are not. On the Y axis, the larger a measure is, the larger the damage averted by it, therefore the larger the benefit or the mitigation or adaptation impact of a measure. Hence, with this figure, each measure can be analyzed in terms of mitigation/adaptation efficiency and cost efficiency and compared with one another.

Figure 36 a) and b) displays impacts of measures applied to assets in USD as in 2042 under a moderate and extreme climate scenario. In the case of flood risk, a large number (15 measures in different location adding up to a total of 22 and three (3) parametric insurance) of measures were selected for the cost benefit analysis.

a) USD Benefits for a Moderate Climate (RCP45)



b) USD Benefits for an Extreme Climate (RCP85)

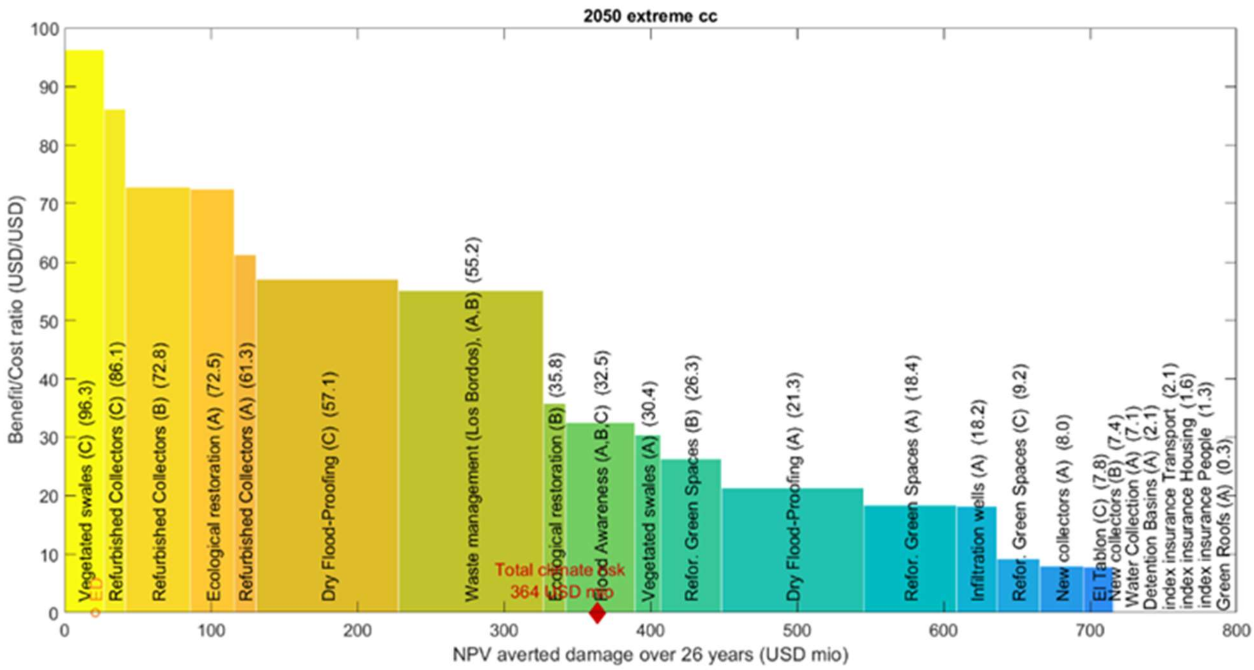
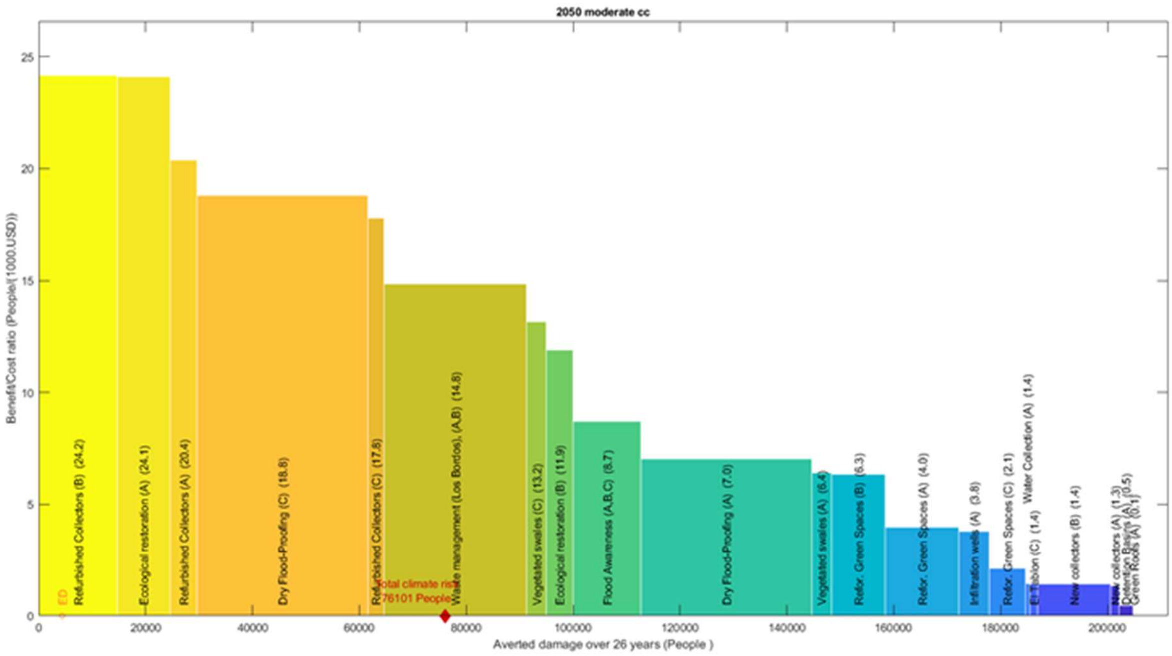


Figure 36 Mitigation cost curve for assets damage inundation in USD a) Moderate Climate and b) Extreme Climate

In Figure 36 a) and b) all measures are cost efficient, with the exception of “green roofs” which return a ratio below one. Altogether and for the time horizon 2042, these measures account altogether to more than 700 Mio USD of averted damage, if combined without overlapping effect. Selected measures offer therefore an efficient adaptation strategy against climate and economic change. Between measures, one can observe large differences in both cost efficiency and benefit (averted damage). For instance, “Ecological restoration” in the upper areas, as a typical green measure, offers both a substantial benefit (> USD 30Mio) and an excellent cost/benefit ratio, where each invested dollars accounts for more than USD 70 of averted damage. In addition, grey measures such as “refurbished collectors” in different zones offer a good alternative to new and expensive infrastructure work such as “new collectors”.

a) USD Benefits for a Moderate Climate (RCP45)



b) USD Benefits for an Extreme Climate (RCP85)

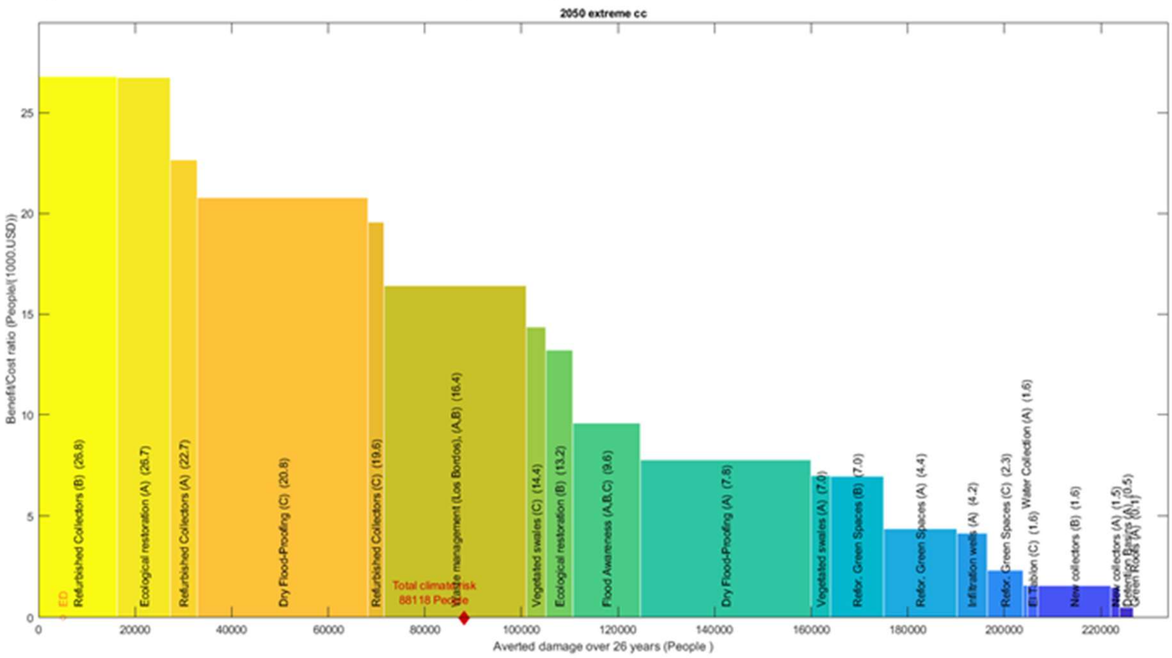


Figure 37 Mitigation cost curve for affected persons a) Moderate Climate and b) Extreme Climate

Other grey measures, such as “dry flood proofing” are typically more efficient in terms of averted damage, but showing a limited cost/benefit analysis for each invested dollar. Interestingly, “waste management” shows a high efficiency and impact for SPS, making this measure worth considering. The measure “El Tablon” is discussed extensively in Chapter 7.3.

Figure 37 a) and b) displays impacts of measures applied to people. The benefit is expressed in averted damaged on people per USD 1000 invested as in 2042 under a moderate and extreme climate scenario. In the case of flood risk, a large number (15 measures in different location adding up to a total of 22) of measures were selected for the cost benefit analysis. Parametric insurance for people are included in people because of the monetary units used for comparison purposes.

In Figure 37 a) and b) all measures are cost efficient, with the exception of “green roofs” and “retention basin” which return a ratio below one. Altogether and for the time horizon 2042, these measures account altogether to averted damaged on more than 200K people (accumulated over the period), if combined without overlapping effect. Selected measures offer therefore an efficient adaptation strategy against climate and economic change. Between measures, one can observe large differences in both cost efficiency and benefit (averted damage). In general, similar measures that were affected for assets are effective for people with the exception of “vegetated swales”. It is explained by the strong effect of this measure on the road network, which is not reflected on the location of people (matching the housing assets). Other grey measures, such as “dry flood proofing” and “waste management” shows similar results as for assets.

6.5 Parametric Insurance

As displayed in Figure 36, Index-based flood insurance is an innovative approach to developing effective pay-out schemes for low-income, flood-prone communities. Index insurance schemes make use of modelling and satellite imagery with other data to predetermine flood thresholds, which could trigger rapid compensation pay-outs. Effective end-to-end solutions will be developed in collaboration with a range of organizations and experts from central and state government bodies, private insurance firms, community-based organizations (CBOs) and nongovernmental organizations (NGOs). Index can be developed for housing and road network. For housing and transport we propose an attachment of 0.5m for a cover up to 4.5m, with a pay-out up to USD 10,000 for people, USD 5,000 for transport and USD 25,000 for housing.

6.6 Spatial distribution of benefits

Figure 38 and Figure 39 show the benefits of a measure, distributed according to the location of the assets that are affected. The benefits are represented by the annual averted damages averaged over a period of 26 year on a certain asset. In Figure 38, we display the benefit of refurbished collectors in different zones for housing. Depending on the initial asset value, the benefit can be different from one asset to the other. Generally speaking, assets with a larger value, for a similar hazard intensity, are expected to show greater damages. Therefore, greater benefits are to be expected on these assets. Figure 39 shows similar results for the asset “road network” (each point represent a 100m section of the road network) for the measures “reforestation” and “vegetated swales”. The assets road network are the one that benefit most from these measures and the total accumulated value of the road network leads to large benefits and cost/benefit ratios for these measures. Additional maps for other measures and assets are displayed in ANNEX 9.

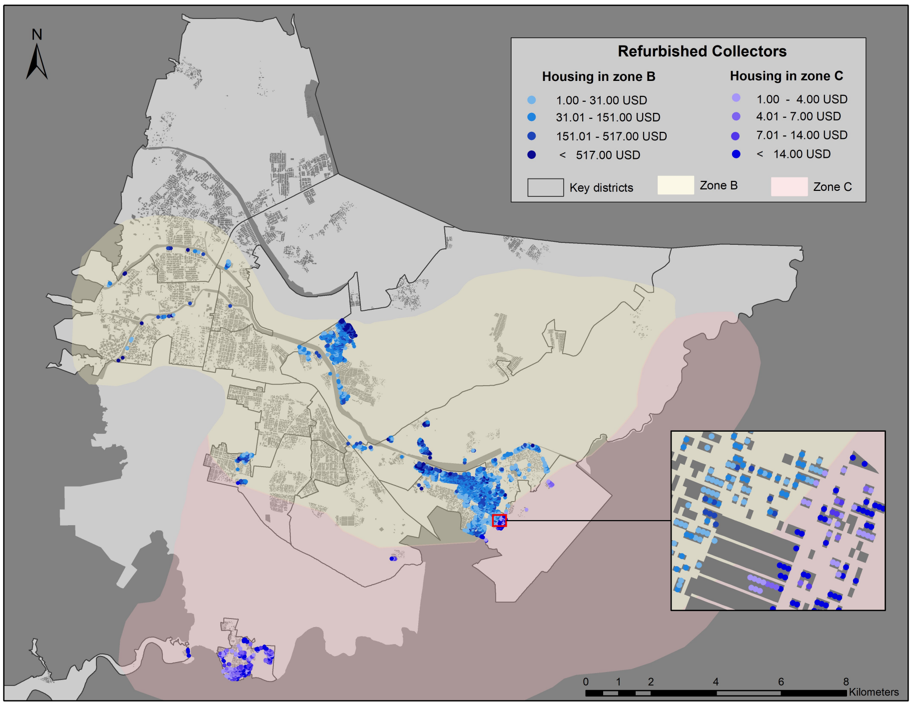


Figure 38 Spatial location of benefits for the measure "refurbished collectors" for housing

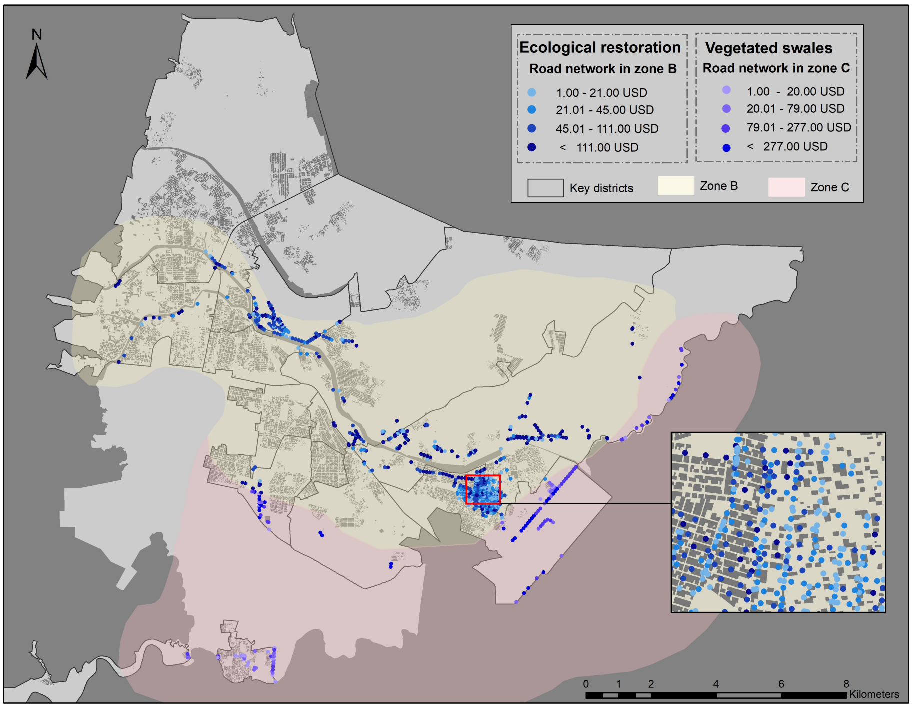


Figure 39 Spatial location map of benefits from the measures "ecological reforestation" and "vegetated swales" for the road network.

6.7 Conclusions

In this section, inundation measures were analyzed in the SPS municipality area (for selected districts) in terms of cost-efficiency and adaptation/mitigation efficiency. A total of 22 measures (14 measures indifferent locations) were successfully introduced in CLIMADA. The main findings are summarized below:

1) A majority of selected measures are cost efficient for the asset selected;
2) All measures combined are sufficient to account for the total climate risk (although without considering storm risk);
3) By 2042 measures for inundation will be more efficient for assets, especially under extreme climate conditions;
4) Low key grey measures and green measures a most efficient;
5) Climate index insurance for Housing, people and road network are all cost efficient and can be used to cover residual risk after the most effective measures have been implemented.
6) The top three measures are:
    a. "Vegetated Swales"
    b. "Refurbished Collectors"
    c. "Ecological Restauration"

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 General Conclusions

San Pedro Sula, as other urban areas in the world are threatened by floods, droughts and other extreme weather events. Along with growing populations and economies, losses from natural hazards are rising. In this report, we applied the Economics of Climate Adaptation (ECA), a decision-making support framework, to integrate climate risk assessments and optimal adaptation solutions.

In its first part, this report recalls decisions made in coordination with all stakeholders regarding the areas of the municipality to be included, the scenarios (climatic and economic) to be applied and what assets should be impacted. During several workshops and webinars, a portfolio of measures (from a long list to a short list) have been discussed. Values have been validated by stakeholder's concertation and expert interview.

Further, this report presents the results, assumptions and limitation of the development of a flood model for the region of the municipality of San Pedro Sula. The flood model developed for the purpose of this report provides unique improvement in resolution and quality to the simulation of flood in the region. Its integration into CLIMADA, a modelling platform, provide an estimation of impacts of future flood risk impact for the selected assets. These results for future damages have been successfully validated against existing historical observations. By 2042, flood damages in the municipality are expected to raise by more than 100% in San Pedro Sula, due both to economic growth (assets will be more valuable) and climate change (hazard will be more frequent and more intense).

The introduction of a selection of adaptation measures provide insights for the development of a sound climate impact portfolio under the selected scenarios. Green measures and grey measures such as channel refurbishment provide the best return on investment, while offering a good protection against future climatic risks. In the following section, we discuss the effects of el Tablon and the need for additional monitoring station in the region.

Finally, the quantification, valuation and parameterization of adaptation measures is a challenging exercise. The location and exact size of an engineering project might influence greatly the cost and benefit calculated. Although great care has been given to the modelling exercise, the outcome of the study are not meant to replace a more detailed engineering screening of the measures to be introduced and offer a decision support, to be added to other tools and discussion already on-going within the municipality. It is important to consider these uncertainties while making climate impact decisions.

7.2 Recommendation for the Monitoring Network

Flood Management processes are driven by natural processes causing possible loss of lives and property. They have the aim to reduce and to avoid the negative effects of flood hazards to the human sphere by assessing the development of specific flood situation.

The UN Office for Disaster Risk Reduction (UNDRR) “advocates the use of Flood early warning systems (FEWSs) as one of the most common flood-impact mitigation measures. […] Comprehensive FEWS consists of four components, which includes (1) risk knowledge, (2) monitoring and forecasting, (3) warning, dissemination, and communication, and (4) response capabilities.”[50]

The occurrence and the progress of specific flood situation itself has to be estimated as good as possible by describing the natural processes with measurements and model simulations to provide a basis for decision makers and emergency relief. Establishing flood warning systems along relevant waterways or water bodies helps to provide critical information for the protection of property and lives. Effective flood warning approaches are composed out of the installation of gages and telemetry equipment and carefully designed procedures to provide early warning about whether a flood is to be expected, when it will occur, and how severe it will be.

Facing this point, measurements of the natural processes as precipitation and discharge are central for an increased preparedness to floods of a city like San Pedro Sula at the confluence of three main rivers with catchments of high relief energy.

In addition to the possible flood warning aspect, continuous measurements and statistical analysis of precipitation, climate data (e.g. temperature, humidity) and discharge will help to understand hydrological behaviour of the catchments better and to monitor undergoing climate change processes within the catchments.

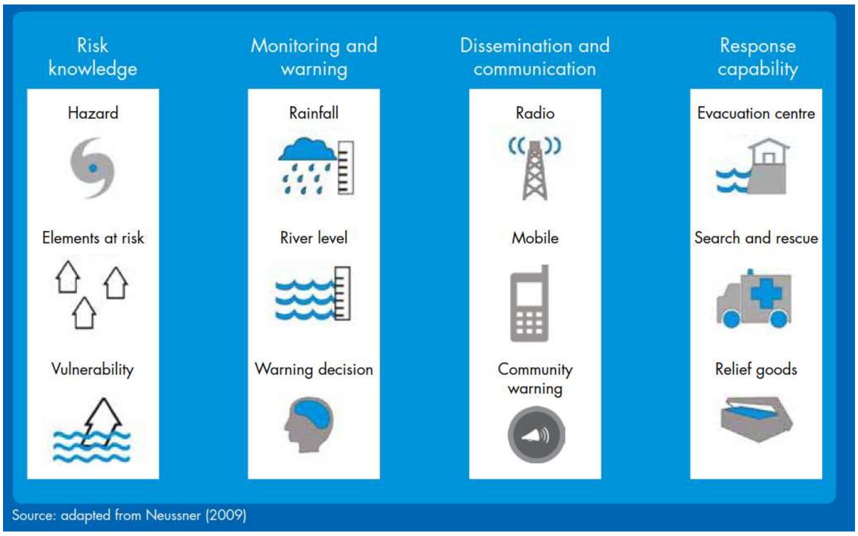


Figure 40 Components of a flood early warning system[51]

[50] Perera, D., Seidou, O., Agnihotri, J., Rasmy, M., Smakhtin, V., Coulibaly, P., & Mehmood, H. (2019). Flood Early Warning Systems: A Review Of Benefits, Challenges And Prospects. Hamilton, Canada: United Nations University Institute for Water, Environment and Health (UNU-INWEH).

[51] Shrestha, M., Kafle, S., Gurung, M., Nibanupudi, H., Khadg, V., & Rajkarnikar, G. (2014). Flood Early Warning Systems in Nepal - A Gendered Perspective. Kathmandu, Nepal: International Centre for Integrated Mountain Development.

Figure 40 presents hydrometric and meteorological monitoring networks which usually include the following components:

1. (Automated) weather station monitoring network / climate data

   Monitoring

   - precipitation (high temporal resolution < 1 h or continuous)
   - additional climate data as temperature, humidity, radiation

   Potential benefits for the river catchment

   - monitoring of time series and statistical analysis (e.g. annual mean, storm duration and pattern, return period/precipitation)
   - monitoring of climate change effects
   - improvement of (sub)catchment behaviour (e.g. discharge volume of sub-catchment and superposition to relevant hydrograph)
   - improvement of Rainfall-Runoff-Calculation and calculation of discharge values for hydrodynamic calculations
   - implementation of early warning systems by alert stations and/or Rainfall-Runoff-Calculation
   - useful for downscaling of (regional) climate model data

2. Stream discharge measurements / gauges

   Monitoring

   - discharge
   - developing discharge rating curve

   Potential benefits for the river catchment

   - monitoring of time series and statistical analysis (Return Periods etc)
   - study of Rainfall/Runoff aspects (e.g. develop ideas about the general effective precipitation in connection to measured precipitation)
   - Modelling improvement and possibility to calibrate/validate models
   - Installation of alert gauge for early flood warning (e.g. triggering eMail dispatch)
   - Management of El Tablon reservoir in connection to precipitation measurements (maybe forecast available) => Management of water volume for flood protection.

To allow the estimation of possible flood hazards and corresponding risks, often model-based simulations are used to create flood hazard maps and to calculate the flooded area and other relevant parameters as water depth, flow velocity, travel time of flood peak or critical water level indicating the need of evacuations e.g. of hospitals or other vulnerable objects. These models rely on data to describe the flow propagation through the river channel. Physical properties are for example cross sections taken from river channel survey to describe the capacity of the river channel to store and to guide the water downstream without flooding forelands. Nevertheless, also hydraulic and hydrological parameters as effective precipitation and discharge volume are important.

One observation out of this ECA study is that the precipitation and discharge measurement network is not dense enough to allow a calibration and validation of hydrological and hydrodynamic models.

Generally, the installation of a measurement network would allow to improve the hydrological simulation e.g. in terms of more reliable precipitation depth applied to the models for the calculation of relevant discharge volumes as well as the more reliable calculation of the hydrodynamic process transforming the discharge volume into a water level. These discharge measurements will ideally be accompanied by a survey of river cross sections (e.g. water body, bridges).

To determine the location and number of monitoring station a more detailed analysis would be needed. Major patterns, should be analysed including:

- main wind directions/storm tracks
- similar reacting sub-catchments,
- analysis of existing HEC-HMS Model (the time of concentration in terms of discharge and superposition of hydrographs)
- topography/exposition
- travel time of flood peak from discharge gauges to San Pedro Sula for localisation of gauge stationing
- needed time for emergency services and protective measures
- first idea about operating warning system
- Reachability / accessibility / connectivity to authorities

Furthermore, sensor technique has to be chosen according to the local condition and determines the corresponding cost. For stream gauge example simple non-contact water-level sensors (Ultrasonic/RADAR) USD 500; Radar can be around USD 3 000. The choice of the technique depends on local conditions that have to be evaluated. Low cost climate station could start from USD 500 for the sensor itself.

Sensors have to be extended with a data collection platform and a system for data transmission (e.g. GSM) and collected within databases and provided to the user via Graphical User Interfaces. These possibilities also have to be evaluated in addition to the above-mentioned location search. Figure 41, shows the principle elements of a FEWS. Within a first study possibilities and costs had to be evaluated according to the requirement for the corresponding station[52].

[52] Further reading: Challenges and Technical Advances in Flood Early Warning Systems (FEWSs) DOI: http://dx.doi.org/10.5772/intechopen.93069

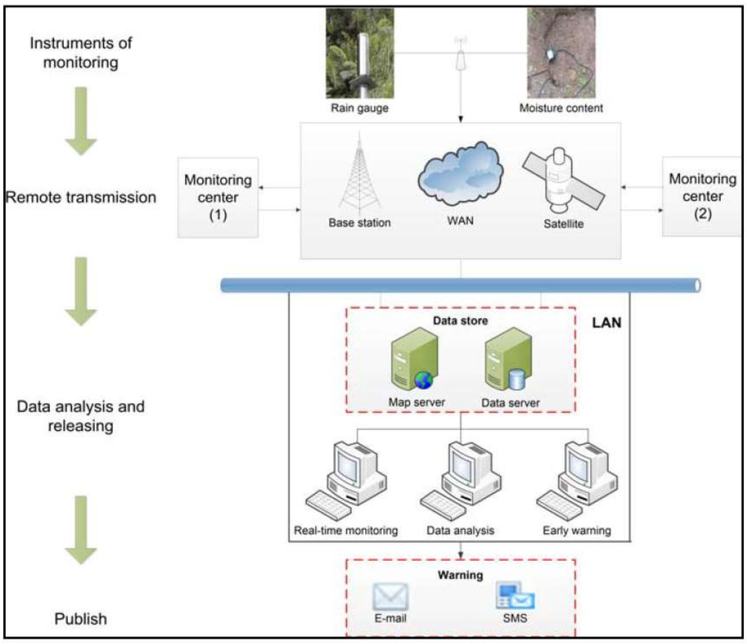


Figure 41 Architecture of the early warning system (modified)[53]

7.3 Recommendation for el Tablón

7.3.1 Modelling of El Tablón Dam

To simulate the effects of the Tablón Dam on the resilience of the Chamelecón River, a hydrological model using the HecHMS software and a hydraulic model with the HecRAS 2D system has been developed. The results allowed to establish of areas at risk under the current conditions for different return periods and to compare them with areas at risk with reduced peak discharges due to the action of the dam. El Tablón was simulated only for future scenarios, which according to what was agreed in the workshops with the Municipality, correspond to the medium (RCP 4.5) and extreme (RCP 8.5) scenarios developed by the IPCC.

7.3.2 HecHMS hydrological model

The input data for the HecHMS model included: 1) the Chamelecón River route, established through the digital elevation model provided by COPECO with a resolution of 1m, 2) infiltration rates according to the curve number method developed by the Soil Conservation Service, which considers uses and types of soil, 3) estimates of the historical depth of short-term precipitation based on the FHIS (2002)[54], and finally 4) projections of future precipitation based on the regional climate model RCA4.

The effects of El Tablón dam were modeled by modifying the hydrological data in accordance with the information provided by the Municipality and presented below:

- Free spillway without intermediate pillars;
- Total length of spillway crest 60 m;

[53] Ju, N.-p., Huang, J., Huang, R.-q., He, C., & Li, Y. (2015). A Real-time monitoring and early warning system for landslides in Southwest China. *Journal of Mountain Science*, 1219-1228.

[54] Manual de referencias hidrológicas de Honduras, elaborado por el Fondo Hondureño de Inversión Social (FHIS) y publicado en 2002.

- Peak level 156 m.a.s.l;
- Maximum level 166 m.s.n.m;
- Maximum capacity approx. 4 000 m3/s.

Tiempo de Retorno	Avenida Pico	Nivel de Embalse	Descarga Pico
Años	m^3/s	msnm	m^3/s
10	1000	158.93	538
20	1330	159.65	767
50	**1880**	**160.61**	**1122**
100	2370	161.39	1450
200	**2960**	**162.29**	**1870**
1000	4740	164.77	3240
10000	8690	168.15	7130
PMF	11300	169.46	10090

Figure 42[55] Downstream peak flow frequency - m3/s

The location of the dam is presented below in Figure 43, including the displacement from the location originally provided by the Municipality to incorporate the effects of the corresponding sub-basin.

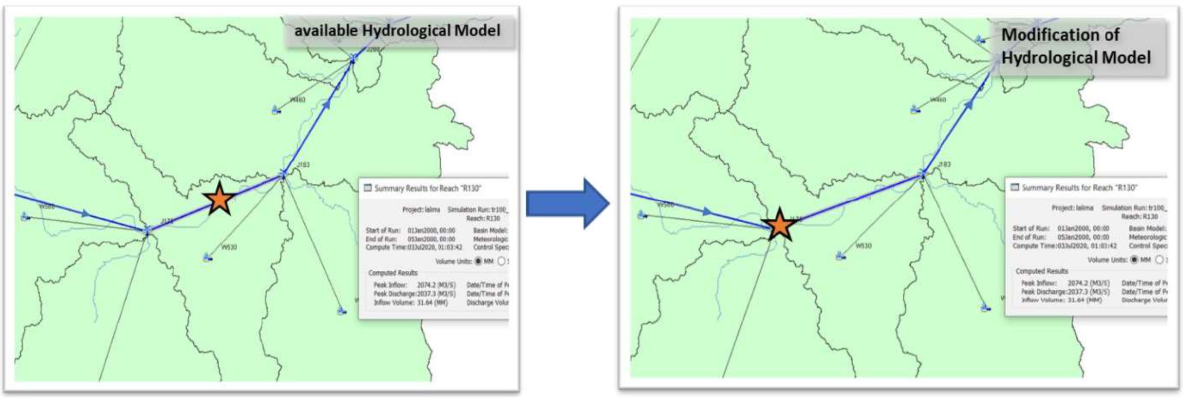


Figure 43 Location of El Tablón Dam in the flood model

Using the data in Figure 42 and the results from the HecHMS model for the Chamelecón River, peak discharges were estimated for the 25, 50 and 100 year return periods, as well as for future scenarios as shown in the figures below. Table 20 presents a synthesis of the peak discharges and the curves show the expected evolution of the discharge. Both illustrations include the effects of the El Tablón dam for future scenarios.

Table 20 Peak discharges in Chamelecón River for return periods (PR) 25, 50 and 10 years, in present scenarios, CPR 4.5 and CPR 8.5

Chamelecón RIVER	PR 25 (m^3/s)	PR 50 (m^3/s)	PR 100 (m^3/s)
Q Present	1 210	1 792	2 108
Q Future Scenario RCP4.5	1 283	1 685	2 213
Q Future Scenario RCP8.5	1 708	2 399	3 470

[55] In comparison, the current capacity of the Chamelecon River in the Sula Valley is 1,900 m3/s.

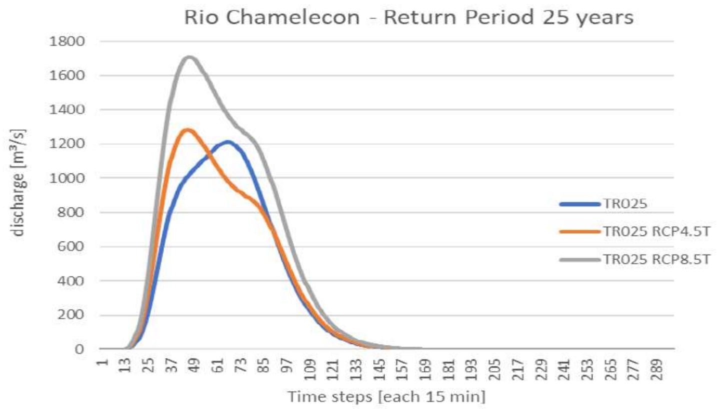


Figure 44 Simulation of Chamelecón River discharges return period 25 years

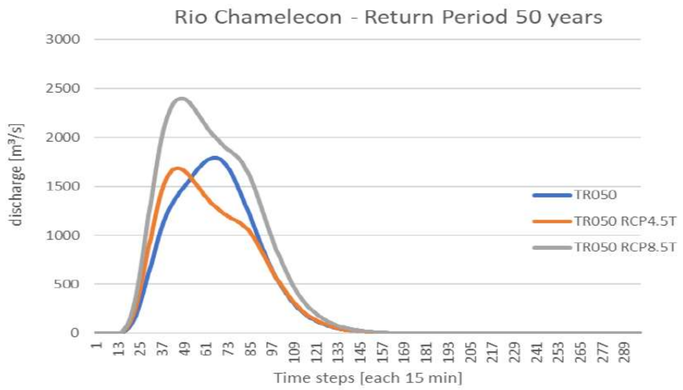


Figure 45 Simulation of Chamelecón River discharges return period 50 years

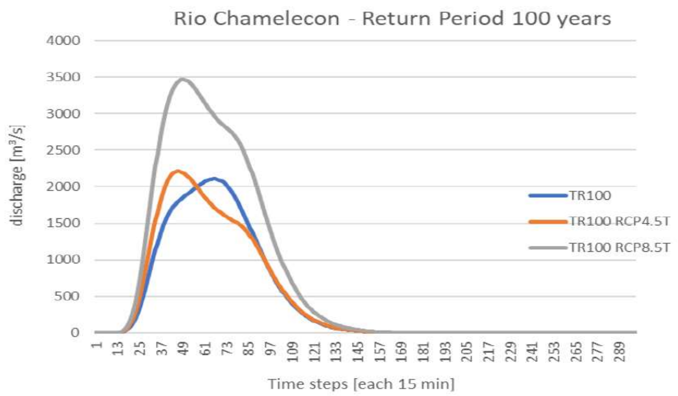


Figure 46 Simulation of Chamelecón River discharges return period 100 years

In this section the estimations of discharge in the Chamelecón River without the El Tablón dam for future scenarios was not included to avoid a misrepresentation of the effect of the dam. In order to have a reliable comparison/validation of the benefits of the dam, further details of the data made available by the municipality are needed including: where the values from Figure 42 come from and how they were calculated, because their validation process was not possible given a lack of additional sources. Additionally, rating curves or/and control units as well as management in the case of flooding are needed. Nevertheless the estimations of discharge are presented in Annex 8.

7.3.3 Validation of the Hydrological Model

Due to the scarce hydro-meteorological measurements (precipitation, runoff, infiltration, discharges, water level, etc...), the validation of the model results was done through third sources. The plausibility check was based on data obtained from scientific literature and by applying Creager envelope curves for extreme floods. The assumptions were also discussed with local authorities in a series of calls.

When comparing the Creager equation (HQ50) with the data estimated by the USGS (USGS, 2002)[56], it was found that the reference values are very different and vary greatly from the available studies. The USGS study examined the "Chamelecón el Puente" station and defined it as unreliable and treats the corresponding values with care. The relationship of the drainage area to the peak flow estimate was also evaluated, calculating a QHQ50 = 2 400 m^3/s while, based on statistical analysis, the QHQ50 measures 1 070 - 2 060 m^3/s. The "Chamelecón el Puente" station is located about 20 km upstream from the exit of the model analyzed in this study.

Table 21 below presents a summary of the values obtained for the validation of the model.

Table 21 Comparison of peak flows between model results, Creager envelope and USGS (2000)

Chamelecón River	Results of the model used for this study (J212) (m^3/s)	Creager envelope curve (HQ50) "Chamelecón el Puente" (m^3/s)	USGS (2000) (m^3/s)
RT= 50	1 792	1 475	2 206.26 (Table 10, p 29)
			1 070 – 2 400 (statistical analysis)
			2 400 (drainage area relation)
RT = 100	2 108	-	1 210 - 2 460

In this regard, the use of the quantitative results of the model are indicative and subject to a significant levels of uncertainty. The model allows a comparison in equivalent terms of the benefits of the different measures analyzed, but a full survey is strongly recommended before local authorities start implementation.

7.3.4 HecRAS 2D hydraulic model

The main rivers of the Municipality were modeled in HecRAS 2D and divided into three sub-models to increase the efficiency of the software as well as the total number of cells and the resulting computational costs of each model. The sub-models contemplate: one the Blanco River, another the Chotepe River and finally the Camelecón River as shown in Figure 47. The Chamelecón river was modeled separately (blue area in Figure 47), incorporating the influence of the Bermejo river as input, due to the extension of the basin and the location of the areas of interest.

[56] USGS: US Arma Corps of Engineers - Hydrologic Engineering Center. (2002): Flood-Hazard Mapping in Honduras in Response to Hurricane Mitch. Water-Resources Investigations Report 01-4277.

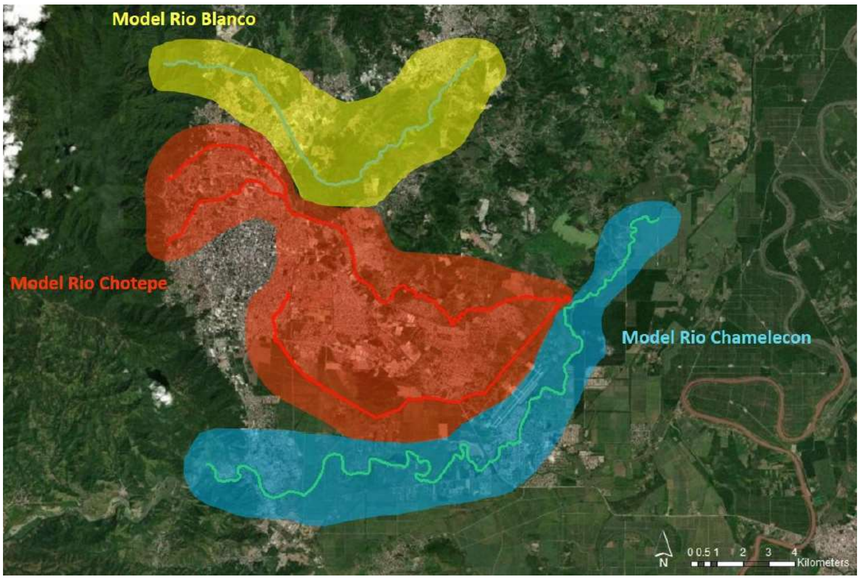


Figure 47 HecRAS 2D Sub models

The basis for the configuration of the 2D model was the 1D models created by COPECO in 2016[57]. These included a digital elevation model (DEM), which was used for the 2D hydrodynamic and instability modeling process. Before creating the HECRAS terrain model, the DEM was analyzed and some impurities and artifacts were identified. Especially the river profiles seemed to be staggered, partially not declining consistently, which was an obstacle to water flow. It was found that the DEM not only represented the terrain, but also included objects of anthropogenic origin, such as bridges. In addition, within the river channel the water surface was not subtracted from the terrain in most parts.

Figure 48 presents the modifications made to the terrain model for the Chamelecón River (marked in pink), to integrate the channel passages and facilitate the flow of water to the Filopo Channel (northwest) and the Maya Channel (southeast).

Figure 48 Modifications of the land model for the Chamelecón River

In terms of the configuration of the model, taking into account the large extension of the Chamelecon River floodplain, a grid was worked with a size varying between 10 and 20 meters. The larger grids were used mainly in flat areas without settlements or infrastructure. Additionally, break lines were

[57] COPECO: Comisión permanente de contingencias. (2016a). Informe V- Hidrología, Producto 1. Análisis de Riesgo a nivel municipal y local, Estimación de Avenidas – Sistemas de cuencas del Municipio de San Pedro Sula Departamento de Cortés. San Pedro Sula.

implemented for each model along the walls, levees and any type of structure that would form an obvious obstacle to flow.

Similarly, due to the overlap of the plain with the other sub-models and sub-basins, the extent of the Chamelecón River sub-model was delimited along the perimeters of the 2D area in some regions. Specifically, the delimitations were made in the southwest by El Calan Creek (normal depth limit condition), in the north by the Filopo Channel that acts as an exit and in the south by the Maya Channel. The exits in both channels were validated based on the results of Suárez (2019)[58], confirming the plausibility of the model.

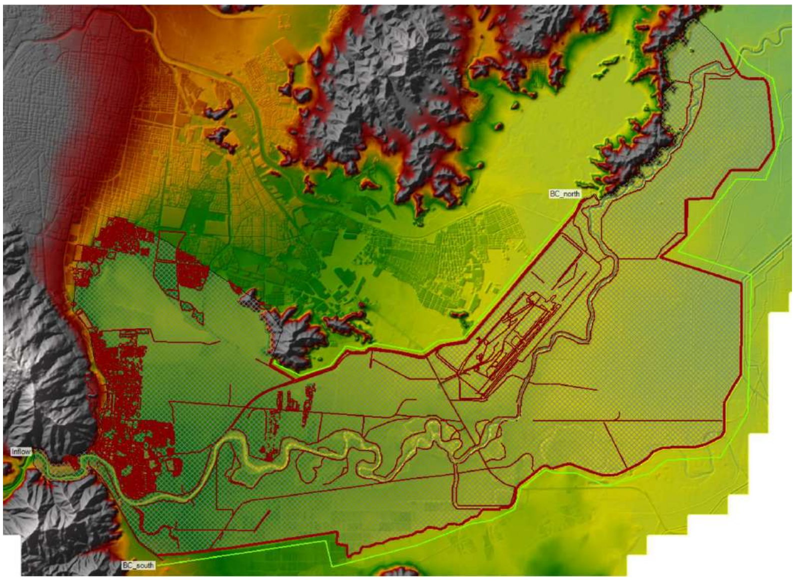


Figure 49 Configuration of the Chamelecon River model, including breaklines (red) and boundary conditions (green)

7.3.5 Hydraulic model validation

Due to poor data availability, it was not possible to validate the results of the hydraulic model. Comparison of the results with the 1998 Storm Mitch flood failed due to lack of data on both discharge and recorded flood plains.

Therefore, the results of the model were compared with the previous studies of Copeco[59], as well as with the thesis of Abrego Suárez (2019)[60]. The available results of the 1D model of these studies confirm quite well the 2D results of this study. Furthermore, Abrego Suarez supported this study with his local expert knowledge and was able to confirm most of the assumptions and results with his experience.

In the Chamelecon River model, the outflow through the Filopo and the Mayan Canal matches well with the discharge values estimated in the Abrego Suarez study (2019).

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[58] Abrego Suárez, C. R. (2019). Actualización preliminar de los umbrales de alerta por inundación de Río Chamelecón en ciudad La Lima, Cortés, para el período de observaciones 2010-2018. Tegucigalpa, Honduras.: Master Thesis.

[59] COPECO: Comisión permanente de contingencias. (2016a). Informe V- Hidrología, Producto 1. Análisis de Riesgo a nivel municipal y local, Estimación de Avenidas – Sistemas de cuencas del Municipio de San Pedro Sula Departamento de Cortés. San Pedro Sula.

[60] Abrego Suárez, C. R. (2019). Actualización preliminar de los umbrales de alerta por inundación de Río Chamelecón en ciudad La Lima, Cortés, para el período de observaciones 2010-2018. Tegucigalpa, Honduras.: Master Thesis.

7.3.6 Results

Below are the differences in floodable areas between simulations with and without the Tablón dam for the return periods described, in the RCP 4.5 scan and for a time horizon of 25 years.

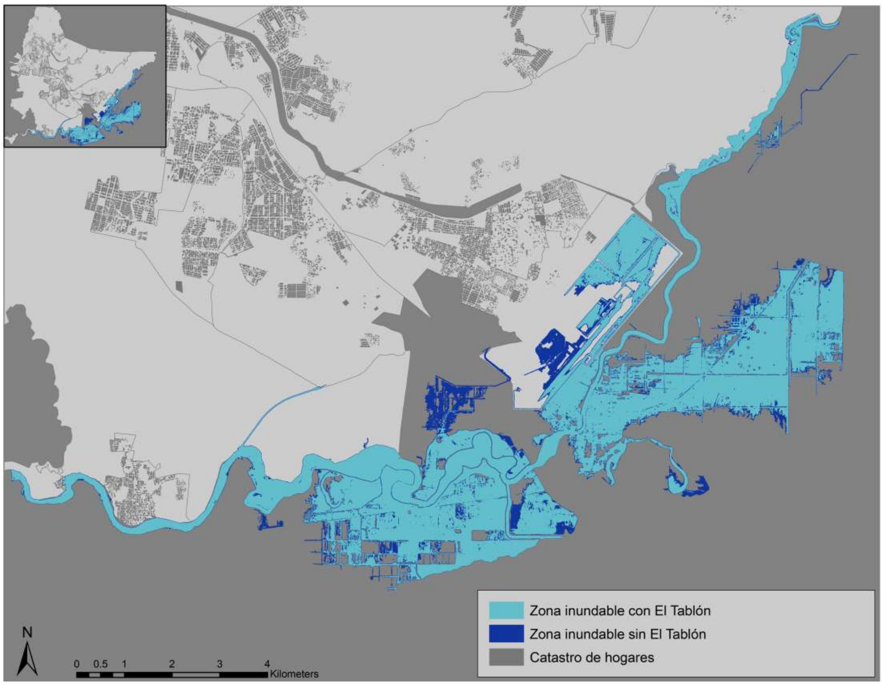

Figure 50 Floodable areas with and without the Tablón dam for a return period of 25 years

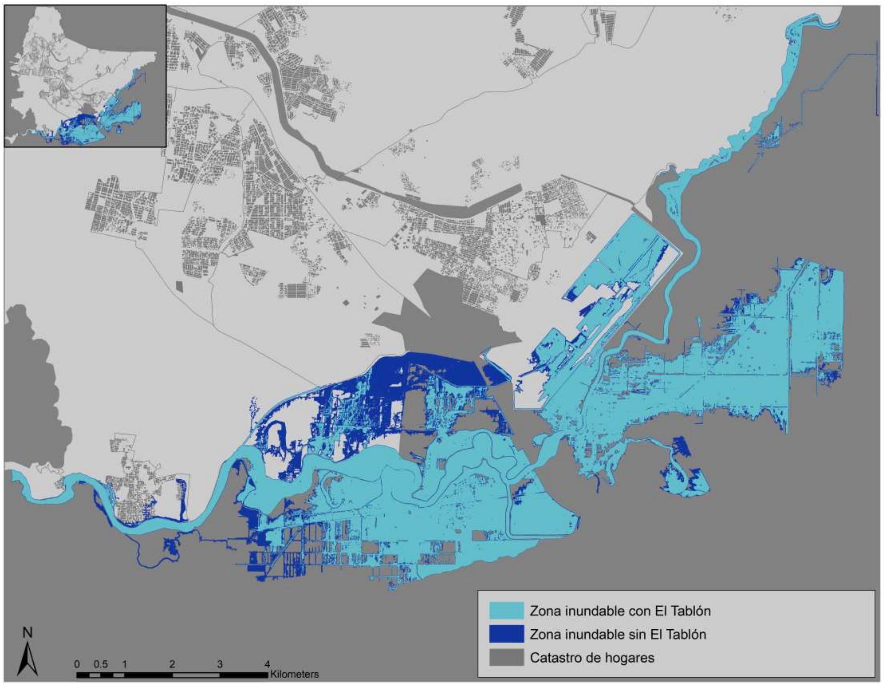

Figure 51 Floodable areas with and without the Tablón dam for a return period of 50 years

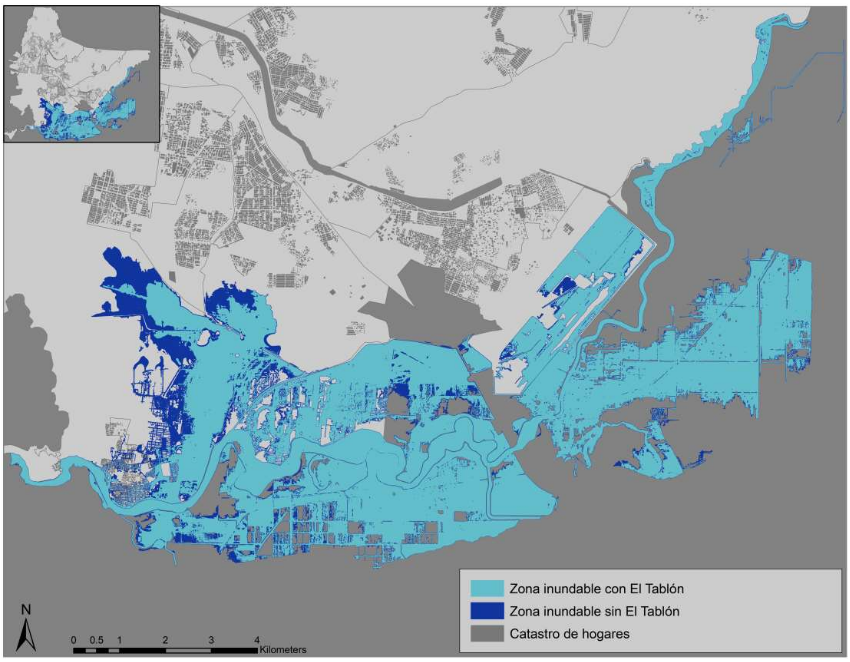

Figure 52 Floodable areas with and without the Tablón dam for a return period of 100 years

Figure 53 presents the changes in the extent of the Chamelecón River floodable areas with and without the Tablón dam. The blue range shows the areas in hectares without the dam and the orange range with the Tablón. In red, the percentage change in areas is observed. It is evident then how the greatest benefits can be expected for less extreme events, such as the 25 and 50 year return periods, and how as the maximum capacity of the dam becomes saturated the percentage reduction in floodable area is less, as in the case of the 100 year return period. The numerical values are presented in Table 22.

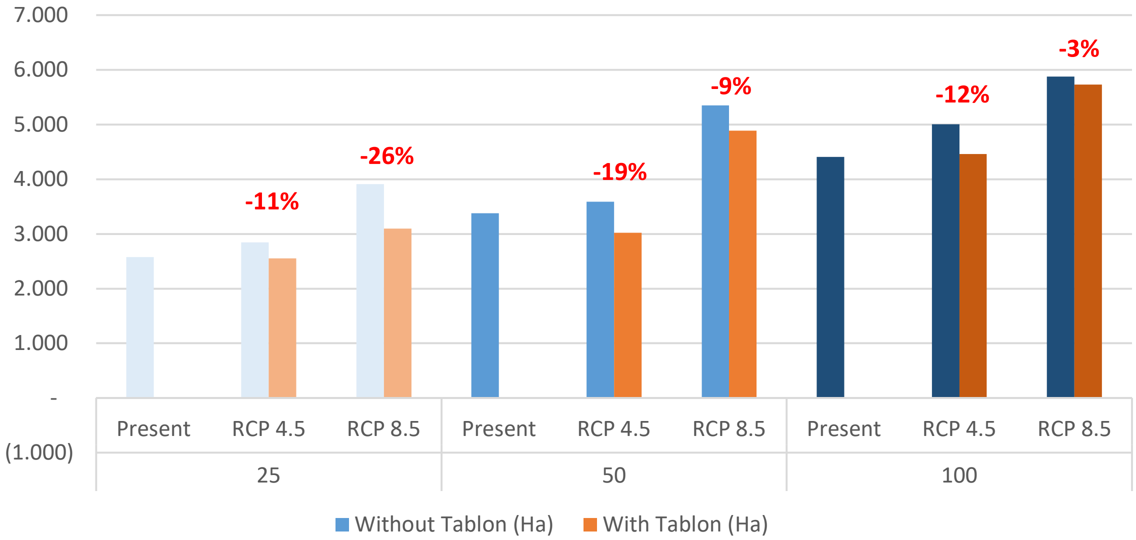

Figure 53 Reductions in floodable areas for return periods 25, 50 and 100 years, for present scenarios, RCP 4.5 and RCP 8.5

Table 22 Chamelecón River floodable areas with and if the Tablón dam

Return period	Scenario	Without El Tablón (Ha)	With El Tablón (Ha)
25	Present	2 578	-
	RCP 4.5	2 846	2 555
	RCP 8.5	3 912	3 096
50	Present	3 376	-
	RCP 4.5	3 586	3 022
	RCP 8.5	5 350	4 889
100	Present	4 406	-
	RCP 4.5	5 003	4 458
	RCP 8.5	5 874	5 729

7.3.7 Conclusions

The result of the Tablón dam modeling shows that its effect on flood extent is much more relevant for minor events. Given the effects of climate change, and the expected increase in the frequency of Eta and Iota type events and even larger ones, our recommendation would be to resize the dam design considering much stronger events than had been predicted in the past.

The challenge of doing such planning with the limited availability of reliable historical hydro-meteorological data is the high level of uncertainty that must be managed when making the corresponding calculations. In this order of ideas, it is recommended to manage strong safety margins in the design of the infrastructure that incorporate the diversity of intensity estimates for return periods available in the literature. The location of the dam may also need to be reconsidered to incorporate changes in design storm intensity.

Additionally, it should be noted that with the exception of the Ramon Villeda Morales Airport, most of the assets and those with highest economic value to the Municipality are located in the city center. The dam effect brings some benefits to this area as it releases capacity for the rivers that cross it to discharge into the Chamelecón during extreme events, but this does not significantly reduce flood risks. The cost-efficiency analysis of the Tablón should then be carried out based on the surroundings of the Chamelecón River and for the other areas of the Municipality, other measures take priority as they have greater effects.

In terms of costing, it is recommended to reconsider the multipurpose character of El Tablón. By focusing the role of the project on flood management and not in energy production, for example, the costs of construction could be significantly reduced, improving the benefit/cost ratio. Similarly by updating the design, which was provided from a 2010 version, other cost could also be optimized and the protective capacity of the project could be improved.

8 PROPOSAL FOR PRE-FEASIBILITY STUDY

8.1 Introduction

This chapter contains the work plan for the pre-feasibility analysis that will be carried out as the last stage of the ECA study on the Municipality of San Pedro Sula. With the goal of facilitating the implementation of the identified adaptation measures discussed in the vulnerability report, the analysis will cover the technical, economic, environmental, social and regulatory frameworks relevant for this case study. These further analyses meets the demands of international donors, such as KfW, to evaluate possible investments.

Regarding the scope of the pre-feasibility study, it will include a: background, beneficiary and feasibility analysis, an institutional analysis of the executing agencies and a budget and execution schedule. The following sections provide some further details.

8.2 Background Analysis

For this study the background analysis covers the institutional context, ongoing programs and initiatives, challenges and opportunities relevant to Disaster Risk Management (DRM) and its interdependence, both at the regional and local levels. These items entail:

- **Institutional context:** Identification of the institutions best equipped to carry out the adaptation measures suggested by the ECA study, in terms of efficiency, effectiveness and accountability. These could be entities from the centralized public sector, from the deconcentrated sector in the department of Cortés or from the municipality of San Pedro Sula, among others.
- **Ongoing programs and initiatives:** Verification of the ongoing programs and activities related to climate change, of the Government of Honduras and the Municipality of San Pedro Sula in cooperation with international organizations, such as the World Bank, the Inter-American Development Bank, the Central American Bank for Economic Integration, the United Nations Development Program, etc.
- **Problems and potentials for DRM:** Preliminary risk classification both in Honduras and in the Municipality of San Pedro Sula and its urban area, through the analysis of available information on flood hazards in the region.

8.3 Beneficiary Analysis

This analysis will include both direct and indirect beneficiaries, considering for aspects of gender, poverty, peace and conflict.

- **Direct beneficiaries:** Defined by local population in the intervention area, and disaggregated by gender, age group, socioeconomic characteristics, etc.
  It will also include the institutions that have received, are receiving or will potentially receive institutional strengthening and actively participate in the implementation of the proposed measures.
- **Indirect beneficiaries:** Constituted by the general population of San Pedro Sula, disaggregated as well by urban or rural location, gender, socio-economic characteristics, etc. Local businesses will also be included, as well as the main existing equipment and infrastructure.

8.4 Feasibility Analysis

This analysis will be carried out to establish the feasibility of at least three of the priority measures proposed by the ECA Vulnerability Report for the municipality of San Pedro Sula. Considering technical, economic, environmental, social and legal aspects.

- **Technical feasibility:** Assessment of the availability of technical and technological means within the Municipality to carry out the measures. The following four topics will be included:
  - Applicable regulations, guidelines of good design practices and other instruments that regulate the technical aspects of the project.
  - Existence of base studies of the land in terms of topography, geotechnics and hydrology, among others.
  - Available technology in terms of accessibility to technological knowledge to implement and operate the measures, as well as the capacity to supply inputs, capital goods including civil work and equipment, labor and maintenance services.
  - Sustainability, which includes the identification of possible failure modes, as well as the ability to obtain funding sources to cover project costs throughout its life cycle.
- **Identification of co-benefits.** Assessment of co-benefits that could occur during the design, implementation and operation of the proposed priority measures. That is, additional positive impacts such as increased employment, increased income, reduction of negative health effects and other qualitative co-benefits, especially in the urban area of San Pedro Sula.
- **Environmental and social risks.** Assessment of possible negative social and environmental impacts that could occur during the implementation and operation of the proposed measures will be identified, as well as the methods available to mitigate or prevent them.
- **Legal feasibility:** Assessment of the current Honduran legal framework that the measures of infrastructure and institutional strengthening, as well as of education-communication and citizen organization that will be proposed in the pre-feasibility study.

8.5 Proposed Executing Entity

In this section, an in-depth analysis of the institution identified as executing agency for the proposed measures and the recommended strengthening needs will be carried out. This analysis will ensure that that such institution has the proven capacity to manage the infrastructure project cycle and citizen management, as well as the adequacy of its procurement and contracting rules and procedures, accounting records and accountability. However, the study will also identify the types of support it needs as an executing agency to successfully implement the proposed measures.

In order to establish the execution structure, a matrix of roles and responsibilities will be prepared to assign these functions to each of the actors involved in the planning, execution and operation of the measures.

8.6 Budget and Execution Schedule

This section will define the scope of the program through a broken-down work structure, to which time and resources will be allocated to develop the schedule and budget for its implementation.

- **Breakdown of work structure:** It will consist of the hierarchical decomposition of the work to be done to achieve the program objectives and the required products.
- **Project schedule:** It will consist of the presentation of all the logical sequence and the steps to be followed to deliver the program's products or results.
- **Program budget:** It will consist of the allocation of the financial resources of the program, to complete and achieve the objectives and products.

8.7 Feasibility Report

The feasibility report will be the final step of the study, for which a vulnerability workshop will be held in San Pedro Sula beforehand.

9 ANNEXES

ANNEX 1 - COPECO: Flood Analysis of San Pedro Sula 2016

ANNEX 2 - ECA: Flood Analysis of San Pedro Sula 2020

ANNEX 3 - Survey Methodological Report

ANNEX 4 - Housing Value Los Bordos

ANNEX 5 - Measure selection procedure

ANNEX 6 - Detailed description of measures

ANNEX 7 - Economic scenario as applied in CLIMADA

ANNEX 8 - Estimations discharge in the Chamelecón River with and without El Tablón dam for return periods 25, 50 and 100 years

ANNEX 9 - Geographical benefit distribution from the adaptation measures

ANNEX 10 - All maps from the report