Deliverable Phase 1 – Climate risk assessment

CLIMAAXKòrsou

Curaçao

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Abbreviations and acronyms

Abbreviation / acronym	Description
CBS	Centraal Bureau voor de Statistiek *Central Bureau of Statistics*
CCCCC	Caribbean Community Climate Change Centre
CDB	Caribbean Development Bank
CRS	Coordinate reference system
DRR	Directie Risico & Rampenbeleid *Directorate for risk and disaster policy*
G&GZ	Uitvoeringsorganisatie Geneeskunde en Gezondheidszaken *Department of Public Health*
KNMI	Koninklijke Nederlandse Meteorologische instituut *Royal Dutch Meteorological Isntitute*
MDC	Meteorological Department Curaçao
NGO	Non-governmental organizations
ROP	Uivoeringsorganisatie Ruimtelijke Ordening & Planning, *Department of Urban Planning*
SOAW	Ministerie van sociale Ontwikkeling, Arbeid en Welzijn *Ministry for Social Development, Labor and Welfare*
SOCC	State of the Caribbean Climate

Executive summary

This deliverable presents the Phase 1 Climate Risk Assessment for Curaçao, developed under the CLIMAAXKòrsou initiative. The primary goal of this phase was to assess the climate hazards heatwaves, pluvial flooding (heavy rainfall), and coastal flooding. Through the integration of global model datasets with the available local data, a foundation for risk-informed adaptation strategies was to be established that support Curaçao's 2050 climate vision.

Given the island's vulnerability due to its small, open economy and densely populated southern coastal areas, this assessment aimed to quantify current risks and identify data limitations that hamper detailed quantitative analysis. The reader will learn about the methodologies applied, the challenges encountered, the preliminary results, and the actions planned for subsequent project phases.

To achieve the goal of this deliverable the CLIMAAX workflows were executed for heatwave, heavy rainfall, and coastal flooding hazards. For heatwave assessment, satellite-derived land surface temperature (LST) data from Landsat 8 was integrated with population vulnerability data (WorldPop) to identify urban hotspots, particularly in Groot-Willemstad, a densely urbanized area. The heavy rainfall analysis utilized alternative rainfall datasets derived from global and regional climate models to estimate extreme precipitation trends using a Gumbel distribution, despite limitations in spatial resolution and localized impact thresholds. For coastal flooding, global datasets (e.g., Deltares Global Flood Maps, Copernicus data) were employed, with necessary adjustments to account for local conditions, though these assessments were constrained by inadequate digital elevation models and land use data.

To tailor the next phase towards stakeholder needs, consultations with experts from the public health, real estate, and financial sectors were held. The feedback from these stakeholders underscored the urgency of addressing risks from extreme heat and heavy rainfall, these hazards disrupt daily life, impact public health, and threaten critical infrastructure. However, the engagement was limited to a few stakeholder groups, prompting recommendations for broader inclusion in future phases, particularly of local community organizations and additional sector specialists.

The key results of this phase were:

- Urban hotspots where high temperatures coincide with vulnerable populations (especially those aged over 65 and under 5), confirming concerns raised by public health authorities.
- An overall increase in the intensity of extreme precipitation events, with spatial variations suggesting a wetting trend in parts of the island and a drying trend in others.
- While current global datasets provide some insight into future water levels, the accuracy of economic and infrastructural risk assessments is compromised by the resolution of the digital elevation models used, and generalized land use classifications.

The work executed under Phase 1 laid the groundwork for Phase 2, where the focus will be on developing new local datasets and refining the existing workflows to produce more precise climate risk maps for integration into the KlimaKòrsou atlas and inform policy development. The progress achieved thus far contributes to the overall project by identifying critical data gaps, informing initial findings with stakeholder input, and outlining clear pathways for enhancing Curaçao's resilience to climate change.

1 Introduction

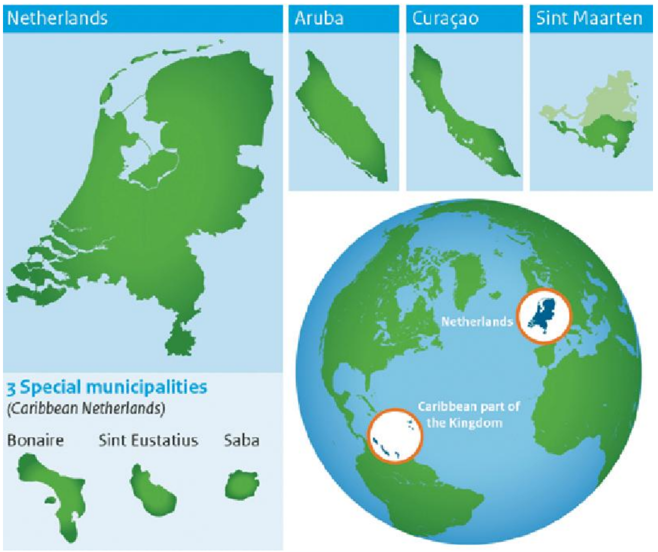


Figure 1-1 The Kingdom of the Netherlands and its constituent countries with The Netherlands situated in Europe and Curaçao, Aruba and St. Maarten situated in the Caribbean.

Curaçao is an autonomous country within the Kingdom of the Netherlands, located in the southern Caribbean Sea, just off the coast of Venezuela. As part of the Caribbean region of the Kingdom, it shares historical and political ties with Aruba, Sint Maarten, and the three special municipalities of the Netherlands: Bonaire, Sint Eustatius, and Saba. Curaçao has a land area of approximately 444 km², and is known for its multicultural society, having Papiamentu, Dutch and English as the three official languages.

1.1 Background

In this paragraph an overview is given of the demographic, governance, social and economic arena of Curaçao.

1.1.1 Demographics

Curaçao has a population of around 155.000 residents. The demographic composition of the island continues to be shaped by migration, with a female-dominated immigration from regional countries such as Colombia, the Dominican Republic, Venezuela and Haiti (CBS, 2024). As of January 2023, the female-to-male ratio stands at 83.2 man per 100 woman. Despite its ethnic and racial diversity, Curaçao maintains strong social cohesion (CBS, 2015). A 2015 assessment highlighted a high level of local pride and a general openness towards others, alongside a shared sense of social engagement and solidarity across different demographic groups. Most people across the island also share a common understanding of moral and ethical values.

Looking ahead, Curaçao's population is projected to continue aging, following a trend observed across the Kingdom of the Netherlands. According to scenarios developed by the Central Bureau of Statistics (CBS), by 2050, the elderly will make up between 23.6% and 30% of the total population, while the share of youth is expected to decline from 19% to between 14% and 17%. Migration will play a critical role in either accelerating or slowing this aging process, with most migrants coming from the Netherlands, Venezuela, Colombia, the Dominican Republic, and Suriname (Bals, 2015).

1.1.2 Governance

Curaçao has broad self-governance in domestic matters but remains constitutionally and strategically connected to the Kingdom of the Netherlands. The Charter for the Kingdom of the Netherlands states that the countries independently manage their own affairs, while together they manage the affairs of the Kingdom. Hence, as an autonomous country within the Kingdom of the Netherlands, the country has its own government, parliament (Staten van Curaçao), and legal system, granting it control over most domestic affairs, including economic policy, education, healthcare, infrastructure, risk and disaster management, and environmental management.

The executive branch, led by the Prime Minister and the Council of Ministers, is responsible for governance, while the legislative branch (Staten van Curaçao) enacts laws that apply exclusively to Curaçao. The island also maintains an independent judiciary under the Joint Court of Justice of Aruba, Curaçao, Sint Maarten, Bonaire, Saba and St. Eustatius with the Dutch Supreme Court (Hoge Raad) serving as the final court of appeal.

Responsibilities pertaining to foreign affairs, defense, Dutch nationality, and judicial oversight remain under the jurisdiction of the Kingdom of the Netherlands, while the Netherlands also retains the authority to intervene in cases of governance deficiencies or financial instability. The countries can support each other upon request, and this is often used in the case of disaster management. While Curaçao cannot independently sign international treaties, it can participate in international agreements through the Kingdom and maintains its own economic partnerships, particularly within the Caribbean.

1.1.3 Social demographics

Available data on inequality in Curaçao indicate a widening gap in wealth distribution, with higher-income groups experiencing increased wealth accumulation while lower-income groups have not necessarily suffered further financial decline. Despite this, economic disparities remain a pressing issue, particularly in the labor market, where the unemployment rate has persisted at approximately 13%, a figure considered high (IMF, 2022).The COVID-19 pandemic, which affected Curaçao from December 2019 to 2022, exacerbated this situation, causing a surge in unemployment that peaked at nearly 20% of the population. However, the labor market rebounded to pre-pandemic levels within a year, largely driven by growth in the tourism sector.

A closer examination of unemployment trends between 2014 and 2022 reveals significant variations across age groups. Youth unemployment has consistently remained the highest among all demographic categories, highlighting persistent challenges in integrating young workers into the labor force (CBS, 2023). Meanwhile, the 65+ age group has shown a notable increase in labor force participation due to changes in policy that increased the retirement age to 65. This rise has also contributed to higher unemployment rates within this demographic (CBS, 2023). Disparities related to gender also shape the labor market, as women represent a larger share of total participants but continue to lag behind men in terms of labor force participation rates (CBS, 2023). Additionally, emigration has played a crucial role in reshaping the workforce, particularly among individuals aged 25 to 64, whose departures have placed increasing pressure on Curaçao's labor market and long-term economic stability (CBS, 2023).

Beyond employment concerns, financial inequality remains a pressing challenge. The 2011 Population and Housing Census revealed that over a quarter of households in Curaçao live below the poverty line, underscoring the persistent struggle faced by many families (CBS, 2022). Furthermore, structural changes in the financial sector, particularly the process of "de-risking," have restricted access to essential financial services, creating conditions conducive to predatory lending practices. Research by Pau (Pau, 2020) indicates that national credit lending has expanded to unsustainable levels, reaching 85% of household income. This rising debt burden has further exacerbated economic vulnerabilities, increasing financial instability and deepening the cycle of poverty for many residents.

1.1.4 Economy

Curaçao's economy is characterized by a small, open structure with several key sectors that drive its economic activity. In Curaçao, three economic pillars can be identified after the closure of the refinery in 2018, which used to be the main economic pillar. Since the closure of the refinery tourism has become the cornerstone of the economy. It generates a significant revenue and creates a wide range of employment opportunities in hospitality, retail and transportation. Another economic pillar of Curaçao's economy is the financial services and offshore banking industry made attractive due to the island's legal regulatory framework and Curaçao's ties to the Netherlands. This sector provides important fiscal contributions through service-related revenues. The third economic pillar is maritime trade that remains an important component of Curaçao'seconomy, though global shifts in the energy markets have affected these industries.

The economy of Curaçao operates its own currency, the Caribbean guilder, and is supported by a Central Bank. This currency is a monetary union between the island of Curaçao and the island of St, Maarten, another country within the Kingdom of the Netherlands.

Curaçao's dependency on the few key sectors mentioned above makes it vulnerable to global economic fluctuations, natural disasters and climate change.

1.2 Main objectives of the project

The CLIMAAXKòrsou initiative aims to enhance Curaçao's climate resilience by integrating comprehensive risk and vulnerability assessments with local data and stakeholder input. This approach will provide valuable insights into the projected mid- and long-term impacts of climate change, ensuring that policy recommendations are well-informed and fostering education and awareness to support the nation's 2050 climate vision.

The specific objectives of this initiative include:

1. Quantifying climate risk assessments to Curaçao's specific geographical context using global model datasets;
2. Integrating the CLIMAAX toolbox for specific hazards with local datasets to generate insights on the geographical and quantitative extent of climate risk.
3. Aligning the project with *KlimaKòrsou*, Curaçao's climate atlas (www.klimakorsou.org), by incorporating the risk and hazard assessment information on this platform to increase public awareness.
4. Developing risk informed adaptation strategies.

1.3 Project team

The project team for the execution of CLIMAAXKòrsou consists of members from the Meteorological Department Curaçao and Climate Adaptation Services. For this phase both institutions provided one member to execute the work.

1.4 Outline of the document's structure

This report is organized in 4 main sections. Chapter 1 provides a background of Curacao's demographics, governance, social and economic situation and the main objectives of this project. The implementation of the CLIMAAX climate risk assessment framework and the obtained results are described in chapter 2. Chapter 3 draws on the conclusions reached after executing this phase of the project, while chapter 4 gives recommendation and outlines contributions to future phases.

2 Climate risk assessment – phase 1

In this chapter the execution of the climate risk assessment based on the CLIMAAX framework is described.

2.1 Scoping

The first step of the CLIMAAX risk assessment framework is the scoping phase. During the scoping phase the objectives, context and stakeholders that need to be involved in CLIMAAXKòrsou were identified. This paragraph gives an overview of this exercise.

2.1.1 Objectives

The CLIMAAXKòrsou initiative aims to enhance Curaçao's climate resilience by integrating comprehensive risk and vulnerability assessments with local data and stakeholder input. This approach will provide valuable insights into the projected mid- and long-term impacts of climate change, ensuring that policy recommendations are well-informed and fostering education and awareness to support the nation's 2050 climate vision.

The specific objectives of this initiative include:

- Quantifying and downscaling climate risk assessments to Curaçao's specific geographical context using global model datasets;
- Integrating the CLIMAAX toolbox for specific hazards with local datasets to generate insights on the geographical and quantitative extent of climate risk.
- Aligning the project with *KlimaKòrsou*, Curaçao's climate atlas, by incorporating the risk and hazard assessment information on this platform to increase public awareness.
- Developing risk informed adaptation strategies.

2.1.2 Context

In the Caribbean, climate hazards, impacts, and risks have been assessed and managed through a combination of scientific research and regional collaborations. Despite these efforts, significant data gaps and capacity challenges continue to limit the effectiveness of climate resilience initiatives. Climate hazard assessments have primarily relied on historical climate data, with some efforts to develop climate projections and scenarios for the wider Caribbean.

One of the key regional resources is *The State of the Caribbean Climate (SOCC)* Report, commissioned by the Caribbean Development Bank (CDB) for its member countries (Climate Studies Group Mona (Eds.), 2020). This report provides critical climate data, analysis, and references to support strategic decision-making for resilience-building. It examines historical and projected climate trends, including temperature changes, rainfall variability, sea level rise, and extreme weather events such as hurricanes, droughts, and floods. However, the effectiveness of these assessments is hindered by the inadequate coverage of meteorological and climatological stations, limiting long-term monitoring and the development of high-resolution climate models.

In addition to climate monitoring, the SOCC examines sectoral impact to evaluate how climate variability and extreme events affect key industries, including agriculture, water resources, infrastructure, tourism, and public health. However, the absence of comprehensive sector-specific data collection has restricted a deeper understanding of the linkages between climate change and socio-economic systems. Risk assessments and decision-making tools have been developed at both national and regional levels, with institutions such as the CDB and the Caribbean Community Climate Change Centre (CCCCC) leading efforts to refine climate risk projections. Nonetheless, the SOCC Report highlights the urgent need for more advanced modeling techniques and impact-based assessments to enhance climate risk management strategies.

Curaçao, situated on the southern edge of the Caribbean, was not included in this regional assessment. However, in 2023, the Royal Dutch Meteorological Institute (KNMI) developed climate scenarios for the Dutch Caribbean island of Bonaire, using station data from Curaçao. Based on these scenarios, a risk and vulnerability assessment was conducted for the harbor in Curaçao (T. Kelder, 2022). Other efforts to quantify climate change risks in Curaçao include a stakeholder mapping initiative conducted by the *Islanders at the Helm* project and qualitative risk analyses by the Meteorological Department of Curaçao.

A key challenge in Curaçao's climate risk management is the limited availability of downscaled, quantitative climate data. This data gap hampers the ability to conduct detailed quantitative analyses of risks, making it difficult to prioritize areas for intervention and focus policy efforts efficiently and effectively. The proposed project seeks to address this issue by developing quantitative risk maps that provide a clearer understanding of climate impacts in Curaçao. This initiative aims to enhance awareness and inform more effective policy and decision-making.

Curaçao has developed a climate strategy roadmap[1] through a comprehensive analysis and participatory approach. The roadmap identifies key sectors that are particularly vulnerable to climate change and outlines strategic interventions to enhance resilience. These sectors include:

- Green Infrastructure – the use of nature-based solutions for climate adaptation.
- Water Management – enhancing integral management of water.
- Coastal Zone Management – Addressing sea level rise and erosion risks.
- Built Environment – Strengthening and improving infrastructure resilience to the impacts of climate change.
- Cultural Preservation – Safeguarding heritage sites and sense of belonging from climate-related deterioration.
- Food Security – Ensuring sustainable agricultural practices and food supply chains.
- Economy and Financial Sector – Assessing economic vulnerabilities and fostering climate-resilient investments.

The overarching goal is to strengthen community and economic resilience, regenerate biodiversity and leverage opportunities arising from climate change.

2.1.3 Participation and risk ownership

Facilitating multi-stakeholder participation is a key step in ensuring ownership in climate impact analysis. This facilitates collaboration among governmental agencies, non-governmental organizations (NGOs), private sector entities, academia, and local communities.

To identify the stakeholders to be consulted in this risk and vulnerability assessment a stakeholder analysis was conducted for heat, coastal flood and pluvial flood. The main stakeholder groups identified for each of these hazards were:

- **Government organizations** i.e. the meteorological department (MDC), the Department of Public Health (G&Gz), the Department of Urban Planning (ROP), the Ministry for Social Services and Welfare (SOAW), the Bureau of Statistics (CBS), and the National crisis and disaster management organization (DRR), play a critical role.

[1] https://www.weather.cw/cccp/Routekaart_Klimaatstrategie_Cura%C3%A7ao_Final_plus_MEO_Final.pdf

- **Non-governmental organizations and civil society** i.e. community-based organizations working with those identified as vulnerable groups for this assessment, environmental conservation groups and organizations working in public health.
- **Private sector and industry** i.e. Construction and real estate developers, insurance and financial institutions, agricultural sector and fishermen as well as the tourism and hospitality sector.
- **Academic and research institutions** i.e. hydrologists, coastal engineers, urban planners and architects, climate researchers outside MDC, public health researchers, economists and social scientists.

The vulnerability assessment framework considers physical, environmental, and human systems. Human vulnerability is assessed based on socio-economic and demographic factors, with priority given to groups that are disproportionately affected by climate hazards, i.e. the vulnerable groups. For Curaçao the following groups have been identified as being vulnerable:

- Elderly and very young populations
- Low-income communities
- Migrants
- Female-headed households

When it comes to risk ownership the Meteorological Department of Curaçao is responsible for conducting climate risk assessments and providing the necessary data for decision-making. The national crisis and disaster management organization is responsible for developing disaster and crisis response plans for the imminent identified risks. Government organizations use MDC's data to develop policies and response measures for the long term, while the private sector, civil society, and academic institutions contribute through research, advocacy, and implementation of resilience-building initiatives. However, given the cross-sectoral nature of climate risks, effective governance of this risk requires the collaboration of multiple stakeholders. To this end, MDC initiated engagement through a participatory process of co-creating the vision and the scope of work that needs to be implemented to ensure that climate risk data inform national and sectoral policies. These groups are brought together in the Curaçao Climate Change Platform.

2.1.4 Acceptable risk

At present, the level of acceptable risk in Curaçao has not been explicitly determined, as the full extent of climate impacts remains insufficiently understood. This project aims to provide the necessary data to establish risk thresholds and inform policy decisions. Currently, the Meteorological Department applies warning criteria for extreme weather events, such as heavy rainfall, heatwaves, and tropical cyclones, based on statistical evaluations of meteorological data and expected impact. However, these criteria must be refined by integrating response capacity considerations and sector-specific vulnerabilities to improve decision-making.

For this project a results dissemination strategy was developed, which includes tailored approaches for different audiences:

- Government agencies and policymakers will be engaged in the elaboration of the results to tailor these results to their needs in phase 1. Furthermore, they will receive data-driven insights to support climate adaptation and disaster risk management policies through the KlimaKòrsou atlas in phase 2.
- Local communities will be engaged to raise awareness of climate risks in phase 2.

- Civil society organizations will be equipped with information to advocate for climate-resilient policies and community action through the KlimaKòrsou atlas in phase 2.
- The private sector will be engaged in the elaboration of the results to tailor these results to their needs in phase 1, and provided with the final risk assessments through the KlimaKòrsou atlas in phase 2.
- Academic and research institutions will contribute to the ongoing refinement of local geographical data.

The results will be validated through direct discussions with experts, and seminars during the first phase. In the second phase stakeholder meetings, and community outreach initiatives will be added to the stakeholder engagement modalities used in this project. This strategy has been adapted in response to the obtained results during the first phase.

2.2 Risk Exploration

This section gives an overview of the risk exploration executed in the first phase of this project.

2.2.1 Screen risks (selection of main hazards)

Curaçao faces several climate-related hazards that directly impact its population, infrastructure, and natural environment. The main climate risks for the island include heat stress, pluvial flooding, coastal flooding, and extreme weather events such as hurricanes and heavy rainfall.

The average temperature in Curaçao has increased by approximately 0.15°C per decade since the first temperature measurements in the 20th century (Girigori, 2011). Projections indicate a further increase of about 2°C by 2050 under a high-emission scenario (SSP5-8.5) (T. Kelder, 2022). This will result in higher maximum temperatures, particularly in the warmest months of September and October, where the average maximum temperature is expected to reach 36.2°C. Historical data also show a very likely (>95%) increase in warm spells and heat waves and in warmer and more frequent warm days and nights. The day-night temperature difference, that is, the difference between the daily maximum and minimum temperature, has also increased since the 1960 (Girigori, 2011). Rising temperatures pose risks to public health, particularly for vulnerable groups such as the elderly and very young populations, low-income communities, migrants, and individuals with pre-existing health conditions. Additionally, key sectors such as water, energy, construction, and the tourism and hospitality sector are also expected to be significantly affected by increased cooling demands and reduced labor productivity due to heat stress. The influence of the El Niño-Southern Oscillation further contributes to increased temperatures for the short term, with El Niño years typically bringing hotter conditions and La Niña years resulting in cooler conditions (Martis, 2001).

Curaçao is also experiencing changes in rainfall patterns. While the total annual rainfall may remain stable or decrease, there is strong evidence of an increase in rainfall intensity and extreme precipitation events (Girigori, 2011). This trend implies an increase in the risk of pluvial flooding, particularly in urban areas where inadequate drainage and extensive surface sealing exacerbate water accumulation. The influence of the El Niño-Southern Oscillation also contributes to rainfall variability, with El Niño years typically bringing drier conditions and La Niña years resulting in increased precipitation (Martis, 2001).

Hurricanes and extreme weather events also pose a risk, although Curaçao historically experiences fewer direct impacts compared to other Caribbean islands. Based on statistical models, a Category 1 hurricane occurs within 250 km of Curaçao approximately once every four years, while a Category 5 hurricane has a return period of 76 years (KNMI, 2023). The impacts of tropical storms and hurricanes can lead to infrastructure damage, disruptions in water supply, and power outages.

Sea level rise presents a long-term risk for coastal areas and low-lying infrastructure. Projections indicate an increase of 24 cm under a low-emission scenario (SSP1-1.9) and 28 cm under a high-emission scenario by 2050. By 2100, this rise could reach 47 cm under a low-emission scenario and 86 cm under a high-emission scenario (T. Kelder, 2022). This will exacerbate risks such as coastal flooding, erosion, and saltwater intrusion, affecting agriculture, water management, coastal communities and the tourism sector. Additionally, the rate of sea level rise is expected to accelerate significantly in the second half of the 21st century.

This risk assessment focuses on three primary hazards:

- Heat stress, which threatens human health, economic productivity, and energy and water demand;
- Pluvial flooding, which increases in frequency due to higher rainfall intensity and urbanization;
- Coastal flooding, driven by sea level rise and extreme high-water events.

2.2.2 Workflow selection

Considering the fact that this analysis is focused on heat stress, pluvial and coastal flooding the workflows for heatwaves, heavy rainfall and river and coastal floods were applied to assess the associated risk.

2.2.2.1 Heatwaves

Heatwaves represent a significant hazard for Curaçao due to their profound impact on daily life and public health. Given the limitations in available data for the "*CORDEX*" and "*XClim*" workflows, the risk assessment for heatwaves was conducted using satellite-derived data. While this approach does not provide insights into how climate projections will influence this hazard in the future, it does identify areas most affected by extreme heat.

The groups most vulnerable to heatwaves include the elderly, young children, low-income communities, migrants, and female-headed households. For this assessment, available global datasets were utilized to evaluate risks specifically for elderly and young populations.

2.2.2.2 Heavy rainfall

For pluvial flooding, both the heavy rainfall hazard assessment and heavy rainfall risk assessments were applied. Though some caution is advised in the interpretation of this data due to the large grid size of the available global and regional model.

Communities most vulnerable to pluvial flooding include residents living in flood prone areas. Areas exposed to this hazard include industrial zones, urban centers, rural communities, and culturally significant sites such as Willemstad, a UNESCO World Heritage site that also serves as the island's governance center.

2.2.2.3 River and coastal floods

For the selected coastal flood hazard, the applied workflow will be coastal flooding and river flooding workflows. River flooding will refer to heavy rainfall driven floods occurring in dry riverbeds. In Curaçao, river floods are not caused by river discharge fluctuations and anomalies, but by heavy rainfall that make the ephemeral streams to resurface. Local conditions of dry riverbeds and extreme rainfall events develop in frequent inland floods, different from coastal floods. The workflow for river flooding was after all not executed in this phase as the dry riverbeds and their behavior were not available in the provided datasets.

The coastal flooding workflow was applied. It includes sea level rise and storm surge events. Communities most vulnerable to coastal flooding include residents of low-lying coastal areas and tourists staying in beachfront accommodations. Areas exposed to this hazard include industrial zones, urban centers, and rural communities. Additionally, Willemstad is particularly vulnerable due to its geographic location.

2.2.3 Choose Scenario

Since CLIMAAXKòrsou aims to support the development of national adaptation strategies through data-driven insights, the initiative focuses on assessing current risks as well as mid- and long-term climate projections under high and low emission scenarios. In this phase of the project, available climate projections under a low-emission scenario (RCP 2.6) and a high-emission scenario (RCP 8.5) are used to understand potential future climate conditions.

The goal is to assess the risks currently affecting the region and project how these risks may evolve in the near and distant future. Comparing the best and worst-case scenarios will provide a clearer understanding of the potential extent of these risks.

2.3 Risk Analysis

The results for the execution of the workflows are presented in this following paragraph.

2.3.1 Heatwaves assessment

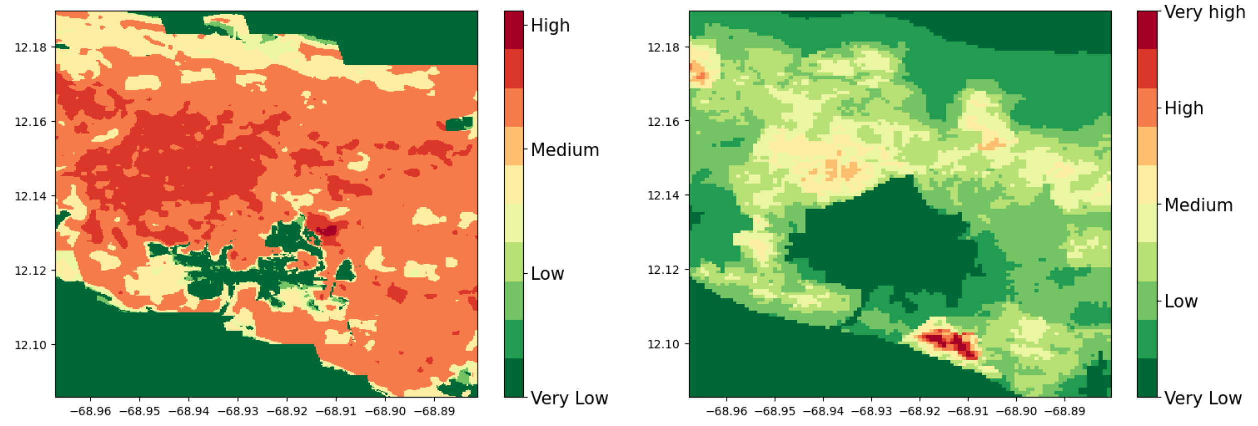
For the heat hazard risk assessment, satellite-derived land surface temperature (LST) data from Landsat 8 was utilized, with a spatial resolution of 15–30 meters and an observation interval of 8–16 days. The analysis covered the period from July 1 to September 30, 2024. This timeframe was selected based on expert analysis of meteorological data for 2024, as well as observed heatwave events during this same period. 2024 was characterized by several heat waves starting as early as June. Additionally, this period corresponds to the climatologically warmest months in Curaçao. Table 2-1 provides an overview of the data applied in the heatwave assessment workflow.

Table 2-1 Data overview workflow heatwaves assessment

Hazard data	Vulnerability data	Exposure data	Risk output
NA	WorldPop dataset on vulnerable population groups for Curaçao (people older than 65 and people younger than 5 years old)	Landsat8 land surface temperature (LST) (spatial resolution: 15-30m; at 8-16 days interval), time frame July 1st to September 30th, 2024.	Vulnerable population exposed to heat hazard

2.3.1.1 Hazard assessment

The selected area for this assessment is the densely urbanized and populated region of Groot-Willemstad, as this workflow focuses on analyzing urban heat islands. Figure 2-1(a) highlights the most overheated zones, while Figure 2-1(b) presents the population density of elderly and young residents, who are among the most vulnerable groups to heat stress.



(a) *(b)*

Figure 2-1 Overheated areas in the area of interest (exposure) based on Landsat data (a) and the population density in the area of interest (b).

2.3.1.2 Risk assessment

In this step the heatwave risk map was calculated based on the exposure (LST - areas that heat up most) and the vulnerability (density of vulnerable population). This risk map is based on 2024 data for the warmest months of the year, where significant heat days were experienced with air temperatures rising to ~37°C. To understand the future risk future climate projections should be evaluated.

Using the risk interpretation map provided in the workflow the vulnerability hotspots, i.e. areas with high possible heat risk, for the elderly (65+ years) and younger (<5 years) population were identified. Figure 2-2 shows this result.

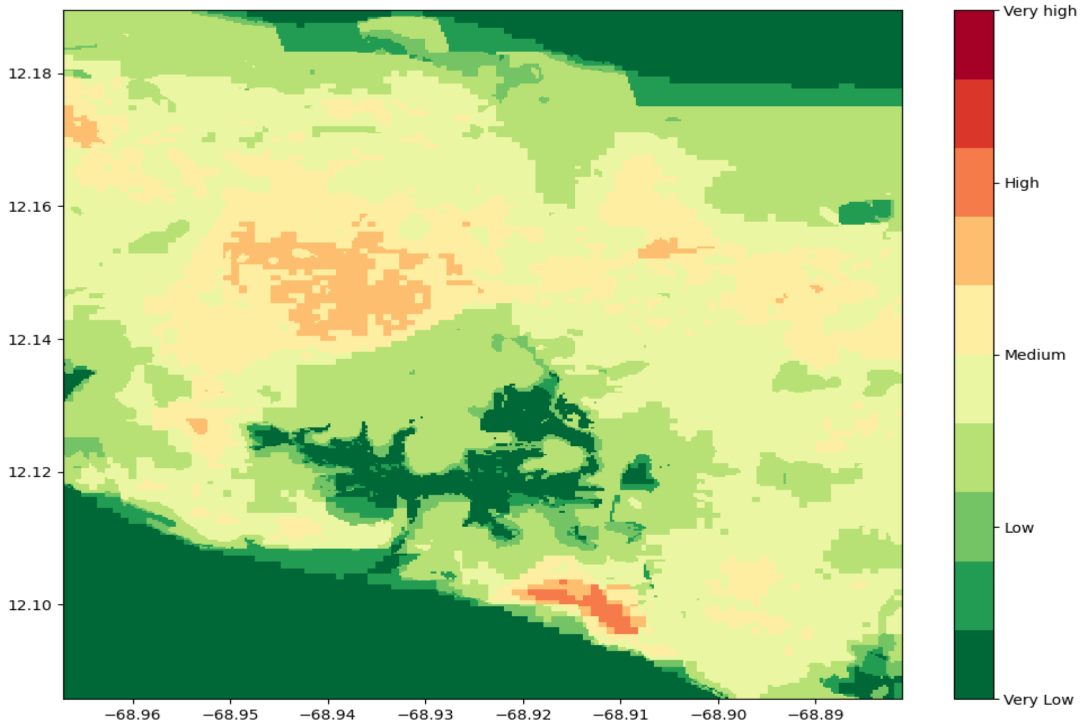


Figure 2-2 Possible heat risk level to the elderly and younger population.

2.3.2 Heavy rainfall assessment

For the heavy rainfall workflows, it was not possible to utilize the pre-calculated EURO-CORDEX datasets, as Curaçao is not covered within these datasets. As an alternative, rainfall datasets representing historical (1971–2020), mid-term (2021–2040), and long-term (2071–2095) periods were generated for the low-emission scenario (RCP 2.6). These datasets were derived using the MOHC-HadGEM2-ES global model (United Kingdom) and the GERICS-REMO2015 regional model (Germany) for Central America with spatial resolution of 0.22 degree .

Curaçao's precipitation patterns are primarily characterized by convective precipitation occurring on a sub-daily timescale. However, given the well-documented limitations of global and regional models in accurately parameterizing convection (Martel, 2021), the workflows were executed to at least provide a preliminary indication of potential changes in precipitation patterns. Furthermore it must be noted that at this stage, no bias corrections have been applied to the datasets. These adjustments will be incorporated in Phase 2 of the project. Additionally, further calculations will be conducted for the high-emission scenario (RCP 8.6) and using other combinations of global and regional models to assess the uncertainty associated with future projections in phase 2.

A significant challenge in conducting the vulnerability assessment is the lack of geographical critical impact rainfall thresholds specific to Curaçao. Without these thresholds, assessing the potential consequences of extreme rainfall events remains difficult. To partially address this limitation and enable a preliminary vulnerability assessment, the reference value for building infrastructure (125 mm/24 hours) was used as a proxy. Further refinements, including the development of localized impact thresholds, will be necessary in Phase 2 to enhance the accuracy and relevance of the assessment.

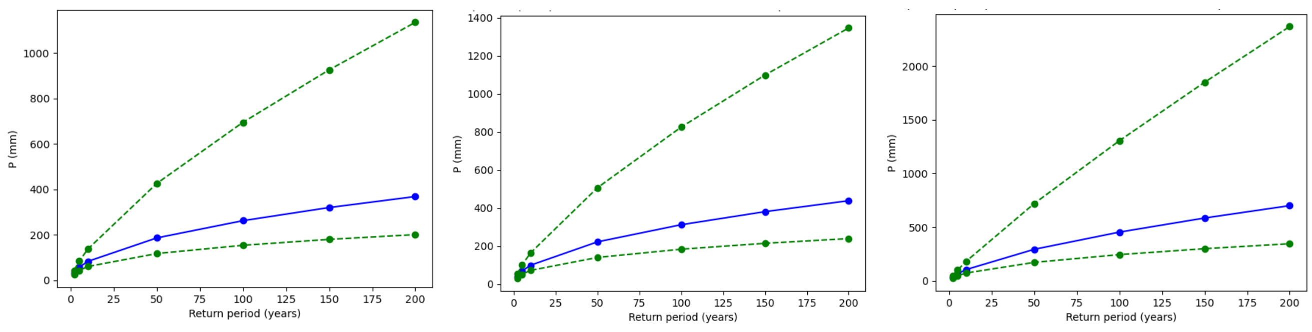
Table 2-2 Data overview workflow heavy rainfall

Hazard data	Vulnerability data	Exposure data	Risk output
Central american Model, global model MOCH-HadGEM2-ES(UK) (RCP2.6), Grid size: 0.22 degree	Not available	Not available	Change in precipitation patterns for different return periods.
Central american Model, regional model GERICS-REMO2015 (Germany) (RCP 2.6)	Not available	Not available	

2.3.2.1 Hazard assessment

For the hazard assessment, the expected annual maximum precipitation associated with a 24-hour duration was extracted for Willemstad. Figure 2-3 shows the projected 24-hour precipitation values for various return periods, illustrating the main fitted curve and the upper and lower confidence interval curves for the short-term (a), mid-term (b), and long-term (c) periods.

The data was analyzed using a Gumbel distribution, as it effectively characterizes the tail behavior of extreme precipitation events, enabling a robust estimation of return levels for different recurrence intervals (Gumbel, 1958).



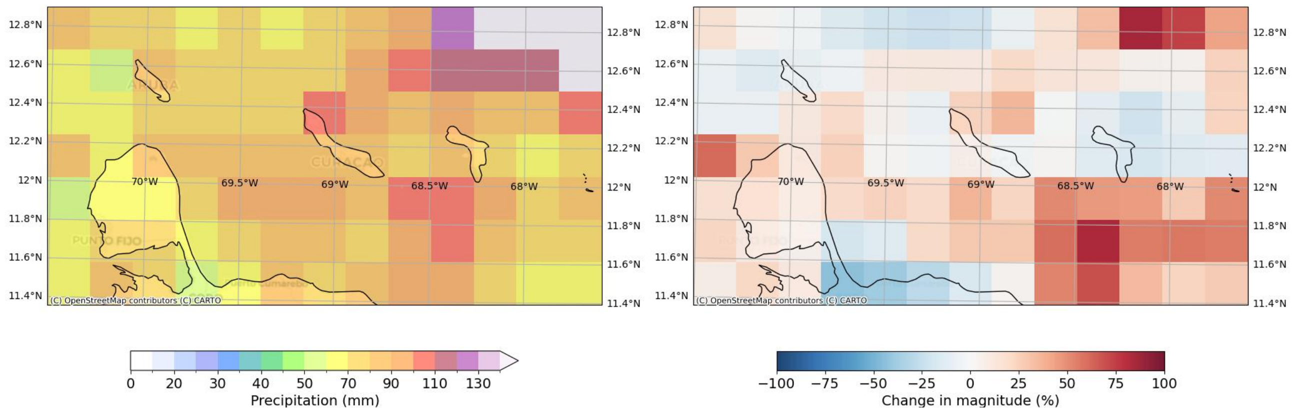
(a) (b) (c)

Figure 2-3 Projected 24-hour precipitation values for the short (a), mid (b), and long term (c), with green the main fitted curve and green the upper and lower confidence interval curves.

For the spatial analysis of changes in extreme precipitation events, the study was extended to a broader geographical area using a bounding box encompassing Curaçao, Aruba and Bonaire. Return periods of 2, 5, 10, 25, 50, 100, and 150 years were selected to assess variations in extreme rainfall across different timescales. The data was again fitted using a Gumbel distribution.

Figure 2-4 shows the spatial distribution of extreme precipitation with a return period of 10 years for the short term (2021-2040). Similar plots were made for return periods 2, 5, 10, 25, 50 and 100 years. An analysis of these results indicate a spatially varying trend in precipitation extremes. In the short term, a wetting trend is observed in the western part of the island, while the eastern part experiences a drying trend. However, in the mid to long term, the trend reverses, with the western region exhibiting a drying pattern and the eastern region showing an increase in precipitation. Over the long term, there is an overall increase in the intensity of extreme precipitation events across the island.

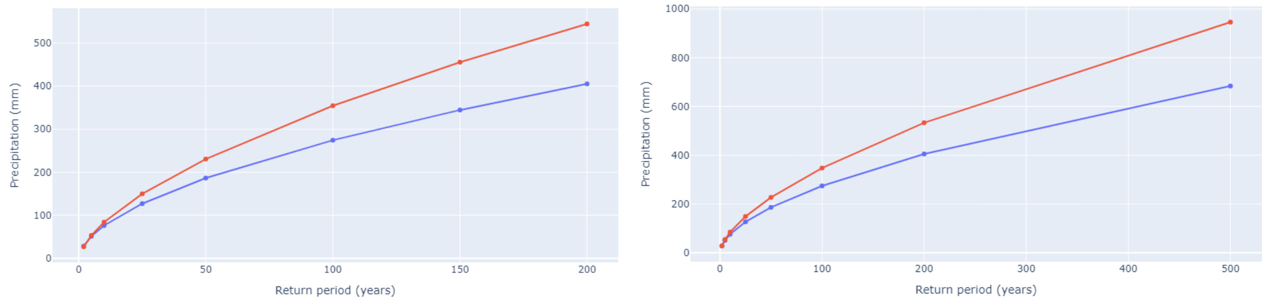
The mechanisms driving these spatial variations are not yet fully understood and require further investigation. Potential explanations may include shifts in large-scale atmospheric circulation patterns like the ENSO, and localized orographic effects influenced by a prevailing wind direction. Additionally, the influence of tropical systems and seasonal weather patterns like the North American cold fronts extending to the South may evolve over time, leading to spatially heterogeneous impacts on extreme rainfall. Further research, incorporating high-resolution climate models and observational datasets, is needed to better understand the underlying drivers of these trends.



(a) (b)

Figure 2-4 spatial distribution of extreme precipitation with a return period of 10 years for the short term (2021-2040) under the low emission scenario (RCP 2.6).

Looking at Curaçao, an increased rainfall intensity for the 24 hour is observed for the short, mid and long term. Figure 2-5 shows the historical 24 hour precipitation versus the calculated precipitation for the mid (a) and long term (b).



(a) *(b)*

Figure 2-5 Historical 24 hour precipitation versus the calculated precipitation for the mid (a) and long (b) term for different return periods.

2.3.2.2 Risk assessment

Due to a lack of geographical availability of the critical threshold, an island-wide risk assessment could not be conducted. Instead a location specific calculation was performed for Willemstad, using the reference value for building infrastructure of 125 mm/24 hours. The results of this analysis are given in Table 2-3.Table 2-3 Change in reference intensity value for infrastructure development using 125 mm/ 24 hours as reference intensity The results indicate a decrease in magnitude for the short term if the 10-year return period is maintained, whereas the magnitude increases in the mid and long term. This trend suggests a growing intensity of extreme precipitation events over time, and hence underscore the need for proactive infrastructural adaptation measures to enhance resilience in the mid and long term.

Table 2-3 Change in reference intensity value for infrastructure development using 125 mm/ 24 hours as reference intensity.

Period	Magnitude Change (%) to Maintain 10-Year Return Period	New Return Period (Years) to Maintain 125 mm Threshold
2021-2040	-2.00%	11.0 years
2041-2060	+17.00%	8.0 years
2071-2095	+23.00%	8.0 years

2.3.3 Coastal and river flooding assessment

For the coastal flood assessments, the workflow was executed using the Deltares Global Flood Maps as the primary flood hazard dataset, which focus on hazard and risk assessments, respectively. This dataset includes extreme water levels resulting from sea level rise, storm surges, and tidal variations. Additionally, global datasets from the Copernicus Climate Change Service were incorporated into the hazard assessment, specifically water level statistical and water level time series data (Copernicus, 2022).

For vulnerability data, the standard European flood depth-damage functions were substituted with Central-South America flood depth-damage functions (Huizinga et al., 2017). This adjustment was made due to Curaçao's geographical proximity to mainland South America, specifically Venezuela. However, upon review, it was noted that Curaçao was not explicitly included in the dataset. Despite this limitation, these functions were applied as they provide a more regionally relevant representation of flood-related damages than European functions.

With respect to the exposure data, the LUISA land use map provided in the workflow was deemed unsuitable for Curaçao, as it only encompasses Europe. Instead, ESA WorldCover 2021 (Zanaga et al., 2022), with a resolution of 10 meters, was utilized for the risk assessment. Additionally, real GDP per capita in Netherlands Antillean Guilders (ANG) was obtained from the Central Bureau of Statistics Curaçao (CBS, 2023), with the most recent conversion to euros (EUR) carried out on March 14, 2025. The datasets used throughout the workflow are presented in Table 2-4.

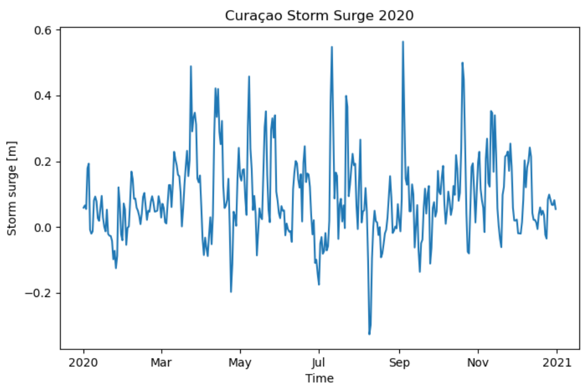
Table 2-4 Data overview workflow coastal flooding.

Hazard data	Vulnerability data	Exposure data	Risk output
Deltares Global Flood Maps	Global flood depth-damage functions – JRC (Joint Research Centre)	European Space Agency (ESA) WorldCover 2021	Economic and Infrastructural damage
Global dataset of water level time series based on reanalysis climate data	GDP/capita (real) – CBS (Central Bureau of Statistics Curaçao)		
Global dataset of statistical indicators derived from the water level time series			

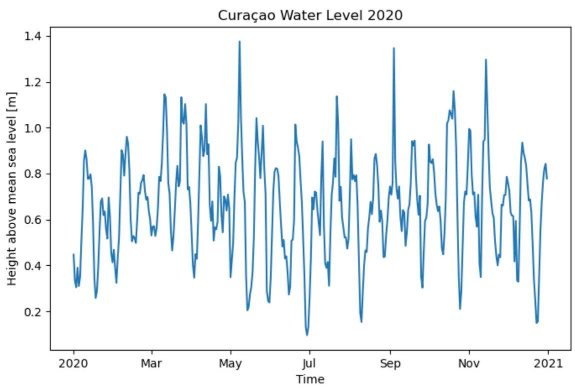
2.3.3.1 Hazard assessment

The hazard assessment on coastal flooding based on water levels first looks at the representative timeseries of water levels and tries to understand the typical range of water level and surge levels at a given location. Furthermore it explores statistics of extreme water levels based on long-term dataset of modelled water levels. Finally it looks at the latest sea level rise projections to understand the range of expected sea level rise and its uncertainty band.

The representative timeseries of storm surge and water levels is shown in Figure 2-6(a) and (b) respectively for 2020. Since both datasets of water level time series and statistical indicators are global datasets, the application of the workflow was possible without any inconvenience.



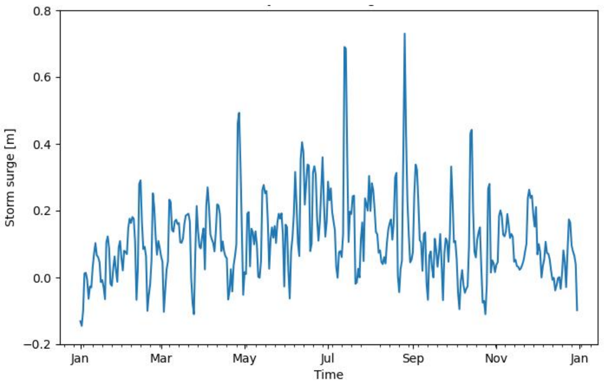
(a)



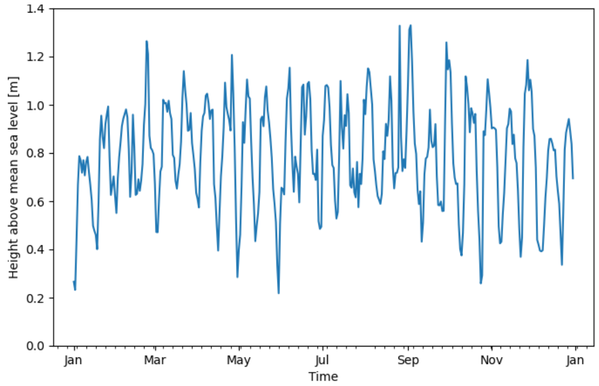
(b)

Figure 2-6 Storm surge levels for Curaçao in 2020 from ERA5 reanalysis data and Water levels for Curaçao in 2020 from ERA5 reanalysis data.

To estimate extreme water levels based on modeled projections, the code was modified to incorporate data retrieval from the GFDL-CM4C192-SST model for comparative analysis. These future projections were available at a 10-minute temporal resolution. Consequently, the code was adjusted to aggregate the data, transforming the 10-minute intervals into daily maximum values. This modification enables a direct comparison between present-day conditions and future scenarios. The projected storm surge and water level time series for the year 2050 are presented in Figure 2-7.



(a)



(b)

Figure 2-7 Storm surge levels for Curaçao in 2050 from future climate projections for storm surge (a) and water levels (b).

Analysis of water level statistical indicators for the historical period (1985–2014) indicates that extreme water levels reached 1.5 meters above mean sea level for both the 5-year and 10-year return periods, while the 100-year return period recorded extreme water levels of 1.8 meters. In contrast, projections for the future period (2021–2050), based on ensemble modeling, suggest a slight increase in extreme water levels. The estimated values for the 5-year, 10-year, and 100-year return periods are 1.5 meters, 1.6 meters, and 2.0 meters above mean sea level, respectively.

The coastal flood maps hazard assessment uses the available precalculated Global Flood Maps dataset developed by Deltares. These datasets are based on global modeling of water levels that are affected by tides, storm surge and sea level rise. This dataset maps the present climate (ca. 2018) and future climate (ca. 2050), with extreme water levels corresponding to return periods of 2, 5, 10, 25, 50, 100 and 250 years. The 2050 scenario assumes sea level rise as estimated under RCP8.5 (high-emission scenario). The flood maps have a resolution of 3 arcseconds (~90 m at Curaçao's latitude)..

For this workflow, it was necessary to adjust the coordinate reference system from EPSG:3035 (Europe) to EPSG:32619 (Curaçao, WGS 84 / UTM zone 19N) to ensure alignment with the region. To assess elevation data accuracy, both the MERIT DEM and NASA DEM elevation models were evaluated, and various year and return period combinations were analyzed to identify discrepancies. The workflow was executed for return periods of 2, 10, and 100 years consecutively. Figure 2-8 shows the selected flood scenarios, illustrating different flood extents for both the present climate and mid-term future scenarios under return periods of 2, 10, and 100 years.

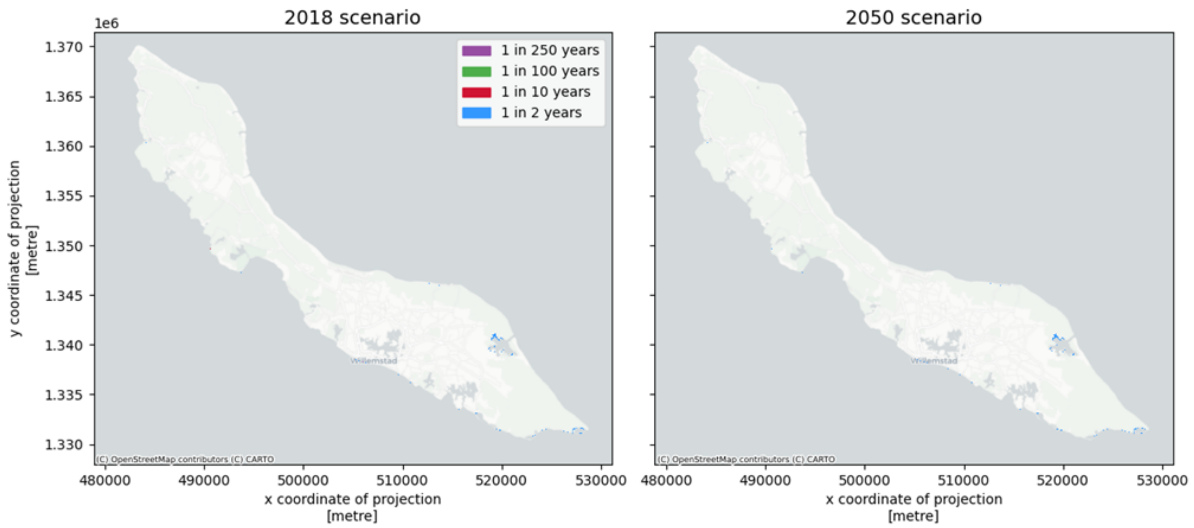


Figure 2-8: Flood extents for Curaçao in 2018 and 2050 overlapped for 2, 10, 100 and 250-year return periods.

As demonstrated here, the Deltares Global Flood Maps and the digital elevation models proposed in this workflow are not suitable for Curaçao. Both the flood maps and the global digital elevation models, MERIT DEM and NASA DEM, lack the necessary resolution to accurately represent flooding dynamics in a small island territory. Both models indicate minimal to no flooding across all available year-return level combinations highlighting the need for higher-resolution, locally calibrated elevation data to improve flood risk assessments.

2.3.3.2 Risk assessment

Finally the flood risk assessment was executed to evaluate the risk to build infrastructure caused by coastal flooding. To do this flood data from the Global Flood Maps (hazard), land use data (exposure), and damage curves (vulnerability) were combined to quantify the order of potential damages in economic terms.

Several modifications were necessary to ensure the applicability of the workflow for Curaçao, ensuring its applicability to the local context. Additionally, extra libraries were incorporated to facilitate the process. This will be described below.

For the hazard assessment, modifications were made to the coastal flood maps by changing the projection from EPSG:3035 (Europe) to EPSG:32619 (Curaçao, WGS 84/UTM zone 19N).

Regarding exposure data, adjustments were made to integrate high-resolution land use data. The code was modified to include ESA WorldCover data at a 10-meter resolution, enabling the processing and merging of raster files. Additionally, the land use coordinate reference system (CRS) reprojection was commented out, as it was no longer necessary given that both the ESA dataset and the bounding box area were already in EPSG:4326. Furthermore, modifications were implemented to ensure that land use classifications were plotted according to ESA WorldCover classifications, as illustrated in Figure 2-9.

The ESA WorldCover provides only a general classification of land use as it differentiates only between built-up areas and various vegetation covers. It hence lacks the detailed infrastructure classifications available in the LUISA land use map for Europe. Furthermore it must be noted that while cropland is indeed scarce in Curaçao, the ESA WorldCover dataset underrepresents its extent, omitting certain agricultural areas that are known to exist in reality.

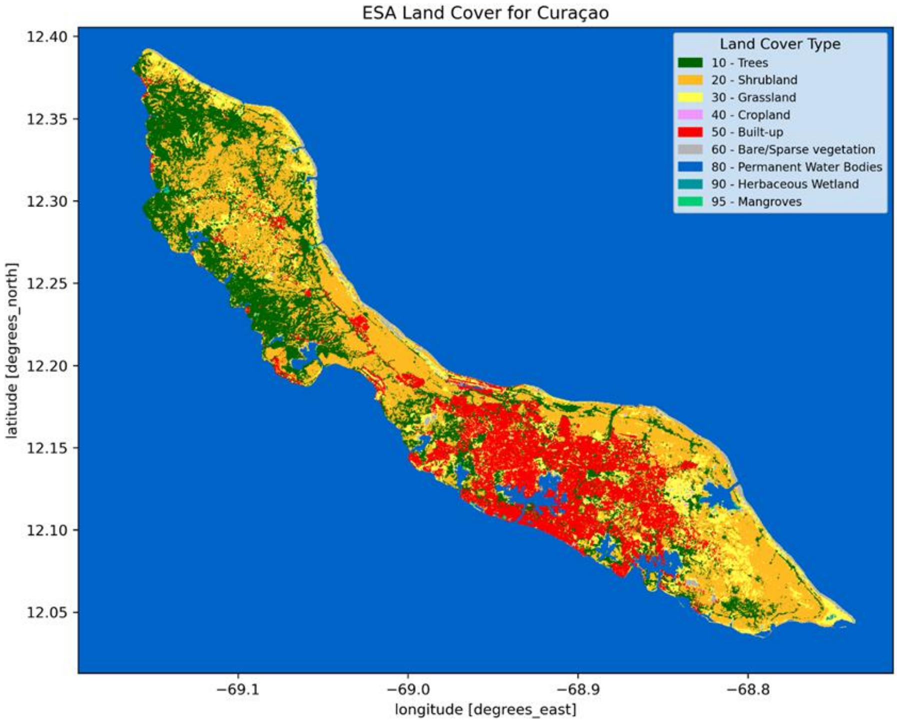


Figure 2-9 Curaçao land use map with ESA WorldCover 2021.

For the vulnerability assessment, modifications were made to the damage curves applied to land use classifications. The input CSV file containing damage curves was adjusted by replacing the JRC European damage curves with those applicable to Central and South America. Additionally, the code was extended to plot damage curves (see Figure 2-10). Damage curve calculations for agricultural and road infrastructure classifications are missing in the Central-South America dataset due to insufficient data.

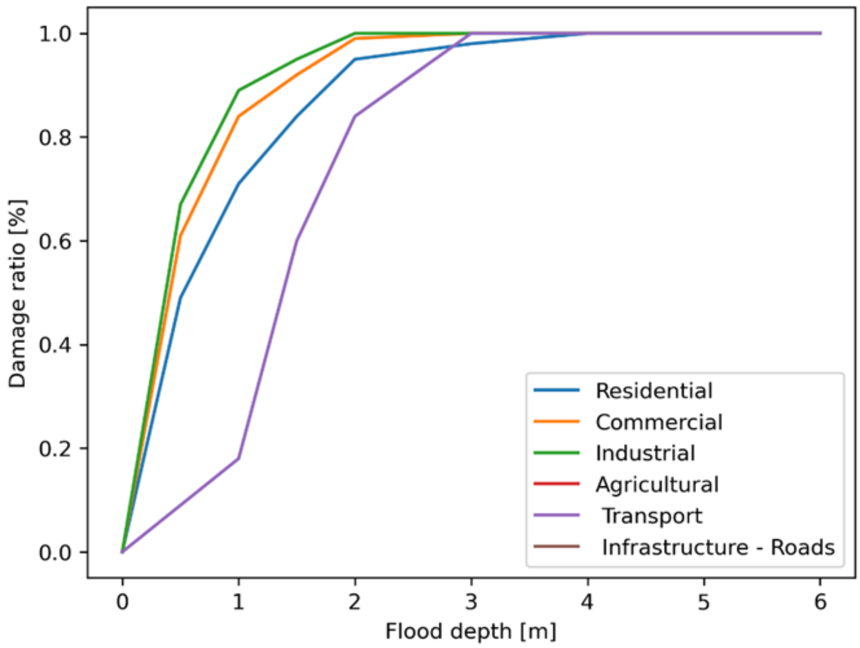


Figure 2-10 JRC flood depth-damage curves in Central-South America.

The new damage assessment curves reveal that infrastructure in Central and South America exhibits greater vulnerability to flooding compared to Europe, since a higher damage ratio is reached at lower flood depths in Central-South America compared to Europe. In the industrial sector, for example, a full damage ratio (1.0) is reached at a flood depth of just 2 meters, whereas in Europe, the same level of damage is only observed at 5 meters. A similar trend is evident in the residential and commercial sectors, where higher damage ratios occur at lower flood depths in Central and South America. This heightened vulnerability is likely due to weaker infrastructure, lower construction standards, and reduced maintenance compared to European counterparts.

It should be noted however, that in contrast to the above findings, the transport sector on the other hand follows a reversed pattern. In Europe, damage ratios are higher at a given flood depth compared to Central and South America, until both regions reach a full damage ratio (1.0) at a flood depth of 3 meters. This suggests that transport infrastructure in Central and South America may initially be more resilient to lower flood depths, while both regions ultimately experience complete damage under extreme flooding conditions.

To adapt the dataset combinations for Curaçao, several modifications were implemented to ensure compatibility with the workflow. The land use map was again projected to EPSG:32619 and saved as a raster file for subsequent damage calculations. Additionally, the flood map resolution was adjusted to match the land use map (10, -10) to maintain consistency in spatial analysis.

For economic damage assessment, an “ESA damage_info_curves” file was created based on the LUISA template provided in the workflow. The formulas and values within this file are derived from the global study by Huizinga et al. (Huizinga, 2022). ESA land use classifications were matched with their LUISA equivalents to facilitate economic damage calculations. Since ESA WorldCover represents all infrastructure under a single “built-up” category, adjustments were made to approximate the proportions of residential (40%), commercial (30%), and industrial (30%) infrastructure in Curaçao. These proportions will be refined further in phase 2, based on input from stakeholders, for a more representative breakdown.

A significant limitation of ESA WorldCover is its broad land classification, which does not differentiate between various types of infrastructure. This limitation reduces the accuracy of economic damage assessments and risk identification. To improve future analyses, phase 2 will incorporate a detailed local land use map with additional classifications to enhance risk evaluation.

Finally, GDP per capita (real) for Curaçao was integrated into the “damage_info_curves” sheet, and all references to “LUISA” in the code were replaced with “ESA” to align with the adapted workflow.

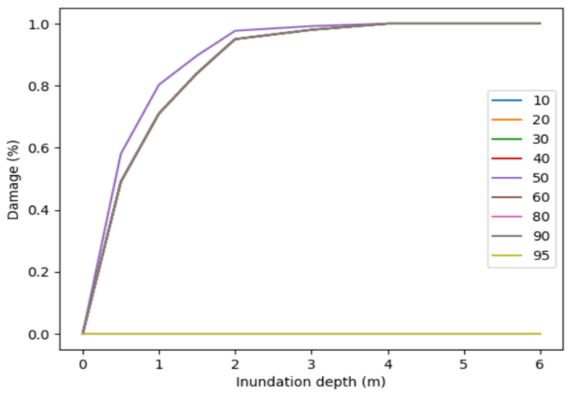


Figure 2-11 Vulnerability curves for flood damages for ESA land use types.

Analyzing Figure 2-11, we observe that agricultural damage curves are unavailable for Central-South America, meaning there is no vulnerability curve for the cropland land use type (40). This results in only built-up (50) and bare/ sparse vegetation (60) are considered vulnerable in this analysis. Furthermore, the projected land use for potential infrastructure damage map was used in the calculations to match the flood map's resampled projection. Damages were then converted from millions of euros to thousands of euros to align with the scale used in the assessment. To ensure consistency with the regional context, all references to "LUISA" in the code were replaced with "ESA."

For visualization, several optimizations were implemented to handle the large datasets efficiently. The lazy loading technique was used, as the files were too large to load in their entirety due to their resolution, and insufficient memory capacity of our hardware. This approach dynamically loads only the required datasets during the plotting process, optimizing memory usage. Furthermore, the code was extended to redefine the ESA WorldCover values and colors to ensure accurate plotting of the damage results.

The results for the risk assessment are given in Figure 2-12. Upon reviewing the results again it is evident that minimal damages were identified in this assessment, primarily due to the limited flooding calculated, which is again related to the lack of sufficiently detailed digital elevation model for Curaçao. Furthermore, it must be observed that the economic damage estimates for ESA are overly generalized, as they rely on a single land use classification to represent built-up areas. This approach assumes that all types of infrastructure are equal, which is not accurate, given the diversity of infrastructure types (residential, tourist, business etc) within built-up areas.

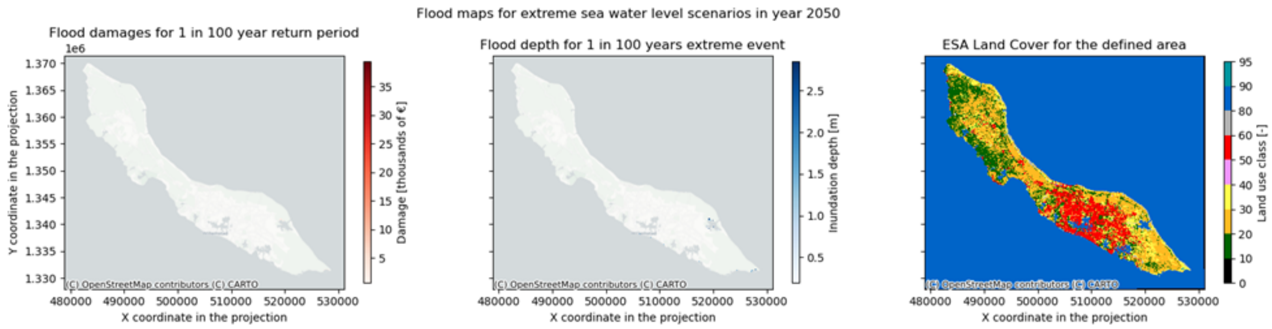


Figure 2-12 Coastal flood damages and flood depth in 2050 for 100-year return period together with land use in Curaçao according to global datasets.

In phase 2 of the project, this risk assessment will be refined further using local data. This involves incorporating a high-resolution local DEM for more accurate flood modeling. Additionally, a more detailed and up-to-date local damage curve and land use map with additional classifications should significantly improve the accuracy of the vulnerability and economic damage assessments, providing a clearer picture of the potential risks.

2.4 Preliminary Key Risk Assessment Findings

The initial risk assessments for heatwaves, coastal and pluvial flooding conducted for Curaçao have revealed several critical insights, despite current limitations in data resolution and future scenario projections. While the available datasets did not allow for a comprehensive evaluation of future coastal flooding or heatwave risks, nor a detailed geographical evaluation of heavy rainfall, preliminary analysis and expert consultations have enabled the identification of improvements that must be considered in the next phase of the project. Discussions with experts from the real estate, financial, and public health sectors, as well as inputs from the Directorate for Risk Management and Disaster Policy (DRR), have provided a clearer understanding of the needs that should be addressed in subsequent analysis.

2.4.1 Severity

The current assessments indicate that, with the current datasets, precise quantitative risk estimates for coastal flooding and future heatwave events are not possible. However, the quantitative approach of integrating satellite-derived heatwave data with global datasets and subsequent stakeholder consultations offered valuable insights.

The satellite-derived data has highlighted potential urban hotspots in Curaçao where high temperatures coincide with densely populated areas of vulnerable group of very young and elderly age. Expert consultations with the Ministry of Public Health, Environment and Nature have confirmed that the population at risk that should be considered in this analysis is indeed the population above 65 years and below 5 years. However due to the high incidence of non-communicable diseases and the impact of heat on these, a subsequent analysis looking at the distribution of populations with non-communicable diseases and a gender differentiation would offer extra information to policy strategies for the ministry. On the other hand, looking at the socioeconomic status, with over a quarter of the population living below poverty, it would be of added value to also look at the low income population and migrants in phase 2 of this project.

With respect to coastal flooding it can be underscored that although current models have not provided a detailed future risk profile for coastal flooding due to data limitations, expert dialogues with stakeholders from the real estate and financial sectors indicate that the impacts of coastal flooding remain a major concern and more information is needed to understand the potential impact on this sector, mainly on real estate vulnerability. To this extent it was highlighted by the experts that new damage curves should be elaborated that reflect the local context in collaboration with the Central Bank of Curaçao and St. Maarten.

2.4.2 Urgency

Based on historic trends, current conditions, and expert input from the public health, financial and crisis management sector, major risks have been identified with respect to heatwaves, heavy rainfall and flooding of vulnerable infrastructure.

For heatwaves it was identified that there is an impact on daily life and the public health. Historical trends show that heatwaves significantly disrupt daily activities, with notable consequences for public health. In recent years, extreme heat has led to school closures in 2023 and 2024, indicating severe impacts on education and overall economic productivity. The labor productivity on the other hand is also influenced. Expert discussions suggest that high temperatures adversely affect labor productivity, particularly in sectors like the construction where outdoor work is prevalent.

With respect to heavy rainfall it was highlighted that economic and structural damage are of great concern. Past events, such as the severe inundations during Tropical Cyclone Tomas in 2010, which analysis showed is an event with a return period of 100 years, resulted in significant economic losses and the tragic loss of lives. Another recent heavy rainfall event in Banda'bou in May 2024, has reiterated the destructive potential of extreme precipitation. Inundation depths of around 2 meters were experienced in the lower areas within this specific catchment area. These events underscored the urgent need for enhanced infrastructure resilience in water management systems.

While the current coastal flooding risk remains under-assessed due to data constraints, it is evident that the high construction density in the coastal areas and the availability of economically productive infrastructure in this area, contributes to economic losses and disrupts critical infrastructure. Adding the urban density further compounds the risk.

2.4.3 Capacity

When it comes to climate risk management measures that are already in place to tackle the risks induced by heatwaves, heavy rainfall and coastal flooding it should be noted that this capacity is supported by different institutional and operational frameworks. The Meteorological department of Curaçao is the legally mandated authority that conducts natural hazard risk assessments. Furthermore it operates a multi-risk early warning system. While the early warning system is not designed to take into consideration changes that may occur over a long period of time, it does encompass extreme events, which for the short term will be more urgent. Additionally there is also a dedicated National crisis and disaster management organization responsible for developing and coordinating disaster response plans.

At the time of an impending crisis or disaster a multi-stakeholder team consisting of government agencies, non-governmental organizations, and the private sector deploys the necessary assistance to the public. This collaborative structure enables information sharing and coordinated actions across sectors. Hence the existing early warning systems and crisis management protocols provide a basis for timely responses to emerging disasters for the short term.

For mid and long term planning purposes however limitations arise. The lack of modelled high resolution data and the availability of localized impact thresholds hinder the application of adaptive measures to mitigate the climate risk.

Mid to long term adaptive strategies that have been implemented already in Curaçao are the application of nature based and grey infrastructure for coastal resilience. A park was created in an area that is historically known to experience extensive flooding due to coastal inundation as a buffer zone. This park hence functions as a recreational area along the coast and a buffer zone that can be sacrificed during coastal flooding caused by extreme events. With the construction of the new medical center a detailed study was conducted. Here again a mangroves park was introduced in front of the medical center to function as a buffer zone for the first wave impacts.

Addressing the risks arising from heatwaves, heavy rainfall and coastal flooding present multiple opportunities in different dimensions. Investment in climate-resilient infrastructure will reduce the physical vulnerability, while if considered during retrofitting, contribute to urban renewal in especially the neighborhoods of social vulnerable groups. Improved building codes and land-use planning on the other hand can lead to safer and more sustainable urban and rural environments while creating long-term benefits of reduced energy consumption and maintenance costs.

Adaptive strategies can furthermore improve public health and exposure to extreme events, as well as create new markets for climate resilient and sustainable technologies. This will eventually lead to skills development and job creation in new sectors.

2.5 Preliminary Monitoring and Evaluation

The initial phase of the project provided several key insights and challenges with respect to climate modelling for Curaçao. While the workflows are nicely structured and provide the premises to do an initial exploratory assessment of the climate hazard and risk, it still underscores the limitations posed by the data resolution and data availability for small islands. In particular, gaps in high-resolution digital elevation models and localized climate projections have limited the ability of the team to generate precise quantitative risk assessments for coastal flooding and future heatwaves with the available data. The lack of detailed, localized impact thresholds for extreme rainfall and suitable damage curves tailored to the local context on the other hand further complicated the vulnerability assessments. For example, while satellite-derived data provided valuable insights into urban heat hotspots, downscaling global climate models to accurately reflect the future projections for the change in heatwaves still pose a limiting factor to calculate the risk. The heavy rainfall assessments also faced difficulties due to the large grid sizes of the available models.

The stakeholder engagement on the other hand with experts has been valuable. Key points of this stakeholder engagement are the confirmation of the urgency of addressing heat and heavy rainfall as priority hazards, as opposed to drought, as these hazards pose immediate risks to public health, education, and economic productivity. While the initial phase engaged a small portion of the stakeholder groups, further iterations during the second phase should consider involving local community organizations to ensure that grassroots perspectives are incorporated, especially related to the local risk perceptions and adaptive capacities. Additional sectoral experts, including specialists in urban planning, transportation, and public health, should also be consulted to refine risk thresholds and adaptation strategies for the third phase. Another group that should be included in future engagements is private sector representatives, particularly from the tourism, and agriculture sector to provide insights into economic impacts and resilience measures.

It has furthermore become evident in this phase of the project that there is a need for enhanced analytical tools and knowledge of methodologies in advanced downscaling techniques and impact modeling. These skills will be essential to bridge the gap between global projections and local realities.

3 Conclusions Phase 1- Climate risk assessment

This analysis reiterated the fact that Curaçao is facing climate risk on the short, mid and long term. The severity of this risk however is not yet fully understood. Stakeholder consultations inform that the heatwaves, heavy rainfall and coastal flooding threaten public health, economic productivity and critical infrastructure in especially areas that experience a high density of vulnerable population. These risks are currently more urgent than drought as initially proposed.

A recurring theme throughout the assessment and in general is the critical role of data quality and downscaling of global datasets for small islands. The limitations in current global datasets due to their large grid size hindered a detailed quantitative risk assessment for future coastal flooding, heavy rainfall and heatwave events in Curaçao. The workflow that suffers most from this limitation is the coastal flooding analysis. While the future water levels can be evaluated with the current data, the geographical exposure and economic risk assessment is hampered by the lack of high-resolution digital elevation models, and limited land use information.

Alternative, for the assessment of the heatwaves risk, datasets like the integration of satellite data on the other hand provided a critical insight in the urban heat hotspots and the vulnerable areas for heat risk considering the young and elderly population. Further refinement is needed to be able to understand the future conditions of this hazard and quantify the future risk for different other vulnerable groups, using where possible gender disaggregated data. This information is highly appreciated by the experts as it informs public policy and the effective deployment of scarce resources, as became evident during stakeholder consultations.

Similarly it became evident that the rainfall models suffer from coarse grid resolutions, while there is an absence of localized location specific impact thresholds and the critical infrastructure data.

Stakeholder engagement during this phase of the project was limited to the financial and economic, and public health sector. This consultation has underscored the immediate urgency of addressing both heat and heavy rainfall, while also highlighting the need for more precise localized damage functions, and impact thresholds to improve the current results. Stakeholders also highlighted the integration of additional perspectives from local community organizations, and additional sector specialists such as urban planners, transportation and the tourism sector to ensure a full spectrum of sensitivity and adaptive capacity is considered.

The capacity analysis also highlighted the need for enhanced adaptive strategies for the mid and long term. While there is an existing early warning system and a disaster management framework that provide a basis for short-term response, this analysis highlights the need for adaptive strategies in the mid and long term. A concise example is that of deploying urban planning as a tool to reduce the exposure of the population to overheated areas.

4 Progress evaluation and contribution to future phases

The team's focus remains in producing geographical climate risk assessment maps for the short, mid and long term, for low (RCP 2.6) and high (RCP 8.6) scenarios to be incorporated in our climate atlas, KlimaKòrsou. The team will hence focus on identifying existing alternative local datasets and developing new datasets to achieve this during the next phase. Table 4-1 shows the datasets that the team has already identified as needed and that could possibly enhance the results for the second phase.

Table 4-1 Data overview for phase 2 of the CLIMAAXKòrsou

Workflow	Hazard data	Vulnerability data	Exposure data	Risk output
Heatwaves	- Downscaled climate projections for RCP 2.6 and 8.6 - Landsat data for the whole island	- Very young and elderly population - Critical infrastructure (retirement homes, hospitals and schools) - distribution of migrant population - distribution of low income population density.	- Overheated areas for the whole island based on landsat data - Projected overheated areas for short, mid and long term, alternatively calculation of the PET ((T. de Nijs, 2019)	- Heat hazard assessment under climate change - Heat risk assessment
Heavy rainfall/ river flooding	- Downscaled climate projections for RCP 2.6 and 8.6	- Critical infrastructure (retirement homes, hospitals and schools) - Damage curves - Land use maps	- High resolution flood depth maps for return periods of 10, 100 and black swan event	Flood hazard assessment. - Infrastructural flood hazard assessment - Economic flood risk assessment
Coastal flooding	- Downscaled climate projections for RCP 2.6 and 8.6	- Critical infrastructure (retirement homes, hospitals and schools) - Damage curves - Land use maps	- High resolution flood maps based on 0.5, 1, 1.5 and 2 meter flooding	Flood hazard assessment. - Infrastructural flood hazard assessment - Economic flood risk assessment

The execution of this first phase highlighted some key challenges that need to be addressed during the second phase of the project as outlined in the monitoring and evaluation paragraph. Notwithstanding these limitations, several milestones and key performance indicators were achieved in this first phase that inform the second phase. Table 4-2 gives an overall overview of the formulated key performance indicators in the work plan, and the overall performance of these

Table 4-2 Overview key performance indicators

Key performance indicators	Progress
At least 2 workflows successfully applied on Deliverable 1. (Achieved)	The team was able to apply the workflow for heavy rainfall, heatwaves and coastal flooding. The workflow for drought was initially also planned in the scope of work. However the team pushed this to the second phase due to the urgency expressed by the stakeholders for the other hazards.
At least 2 workflows successfully applied on Deliverable 2.	Not applicable at this time.
3 stakeholders meetings (2 meetings in phase 1, and 1 meeting in phase 3) (Partially achieved)	A presentation focusing on among other the results of the CLIMAAX workflows was held for the financial and economics sector for the "Island in transition" event during the Green Week. Furthermore an expert discussion was held with the Ministry of Public Health, Environment and Nature to get an idea on the impact of heatwaves and the sensitive groups. The team was unfortunately not able to have the stakeholder meetings as planned for the coastal flooding results due to the quality of the results. A second presentation to experts in the public health sector for the Dutch Caribbean is planned in the 2nd week of April 2025. This will provide more input into the capacity of this sector.

Key performance indicators	Progress
At least 2 publications of new maps in the Klima Korsou Atlas (Nor Achieved)	The produced vulnerability maps during this first phase of the project are qualitatively not suitable to be able to publish in the KlimaKòrsou Atlas.
At least 15 stakeholders involved in the project activities (Achieved)	There are currently only 2 stakeholder groups involved in the project. The presentation during the green week exceeded the 15 stakeholders. However as already mentioned in the second phase the stakeholder groups will have to be adapted to get a more comprehensive socio economic and environmental risk analysis.

Table 4-3 gives an overall overview of the milestones proposed in the work plan, and the overall performance of these.

Table 4-3 Overview milestones

Milestones	Progress
M1: Test of the workflow for flood made.	The workflow for flood hazards was successfully applied for heavy rainfall (pluvial flooding) and coastal flooding. The quality of the results however need to be improved with high resolution data.
M2: Workflow for drought successfully applied.	The workflow for drought was not applied during this phase.
M3: Workflow for heatwave	The satellite based workflow was successfully applied, but needs to be extended with the information on critical infrastructure.
M3: 3 Stakeholders meetings done in phase 1	The stakeholder meetings were not executed as planned due to the limited results achieved with the workflows. Expert sessions and a presentation during the Green week were instead held to still get the stakeholder perspective.

5 Supporting documentation

- Deliverable Phase 1 – Climate risk assessment
- Adapted workflow Heatwaves
- Visual Outputs Heatwaves.
- Adapted workflow Heavy Rainfall
- Visual Outputs Heavy rainfall
- Adapted workflow Coastal flooding
- Visual Outputs Coastal flooding
- Dataset ESA damage_info_curves

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