IVM Institute for Environmental Studies

The Vulnerable Future of Bonaire

A direct climate damage assessment of the built environment of Bonaire

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Summary

This study aims to identify the extent to which Bonaire's buildings and critical infrastructure will be directly impacted by future climate change, focusing on floods and storms. To do so, we combine open-source information on exposure and vulnerability with locally acquired detailed information through interviews and fieldwork. We introduce a new method, called neighbourhood sampling, to produce accurate local data on building values to overcome data scarcity. The results show that in 2050 a 1/100 flood event may affect at least 54 buildings, depending on the climate scenario, most of which are residential along the southern coastline, leading to a maximum of 14.4 USDm in damages. In 2050, no critical infrastructure other than roads will be hit by a flood. Using our approach, we find no damages due to storm hazards, which can be attributed to the limited availability of knowledge on wind vulnerability for Bonaire. The results are assumed to be underestimated due to inaccuracy in the applied hazard intensity maps, which can significantly impact the estimated flooding damages and associated costs. This research is anticipated to serve as a foundation for more sophisticated local climate hazard research on scarce data locations, and Bonaire specifically. Moreover, it provides a starting point for further research on adaptation measures on Bonaire, as it shows which areas are most vulnerable to flooding.

1 Introduction

Global research shows that climate change will cause sea level rise (SLR) and extreme weather, causing severe impacts on humans and livelihoods (IPCC, 2021). Yet, local research to understand the potential impacts of climate extremes is still missing in many parts around the world. Small Island Developing States (SIDS) specifically lack specific local research on how climate change affects them, providing them with less knowledge on how to adapt to its effects (McSweeney *et al.*, 2010). Furthermore, SIDS are widely regarded as highly vulnerable to climate change because they face more environmental challenges than others due to their small size, remoteness, and high exposure to natural hazards (Scandurra *et al.*, 2018).

It is expected that under 2 degrees of global warming by the year 2150, approximately 500,000 people living on SIDS will have to relocate due to permanent inundation. (IPCC, 2018; Rasmussen *et al.*, 2018). Recent research found that climate change is causing more and more health-related risks for SIDS (Schnitter *et al.*, 2018; Ault, 2016). In addition, it may significantly impact the tourism-led growth of SIDS, which most of these islands heavily rely on (Seetanah & Fauzel, 2019). The 2017 North Atlantic Hurricane Season is an example of the impact that natural hazards can cause on Caribbean SIDS. It caused mortality and relatively large-sized population displacement (Robinson, 2020). Bonaire faces, similarly to SIDS, major challenges such as unilateral dependency on tourism, dependency on trade infrastructure, adaptation to sea level rise, and extreme weather events (Verweij *et al.*, 2020). Bonaire’s dependence on tourism and international trade makes it more vulnerable to becoming economically unstable as a result of natural disasters and climate change (EPA, 2017; Koch *et al.*, 2015; Bueno *et al.*, 2008).

In 2016, Hurricane Matthew passed Bonaire at 225 kilometres, causing tropical storms, extreme wind and rainfall, and high waves (KNMI, 2016; Monna, 2016). Recent research shows that sea level rise on Bonaire will be faster than the global average (Le Bars *et al.*, 2022). As a result, Bonaire will likely be hit harder by tropical storms and floods. Especially the south of Bonaire, where most of the housing and infrastructure are located, is vulnerable to climate hazards due to its relatively low altitude. However, most studies on climate impact on Bonaire focus either on tourism or biodiversity instead of direct human impact (UYARRA *et al.*, 2005; Moore, 2010; Sandin *et al.*, 2008; Bak *et al.*, 2005; Debrot & Bugter, 2010).

This study aims to identify the extent to which Bonaire's buildings and critical infrastructure will be directly impacted by future climate change in 2050 and 2150, focusing on floods and storms. To do so, we combine open-source information on exposure and vulnerability with locally acquired detailed information through interviews and fieldwork. We introduce a new method, called neighbourhood sampling, to produce accurate local data on building values to overcome data scarcity. The combination of buildings and critical infrastructure damages provides a complete overview of the expected direct impacts (Garschagen *et al.*, 2016). This research will contribute to a larger research project to create awareness among policymakers and researchers on the dangers of climate change for islands like Bonaire.

2 Methods

This section will elaborate on the methods used in this research to come to the final results and explain the collected data. Furthermore, it will provide information on the different data sources and how they are combined to create the total risk for buildings and critical infrastructure. Figure 1 presents a schematic overview of the methods used in this research, a more detailed schema can be found in Annex A. In this study, a traditional risk approach is applied, in which we define risk as the function of hazard – the probability of a flood event; exposure – the population and value of assets subject to flooding; and vulnerability – the capacity of a society to deal with the event (UNDRR, 2015).

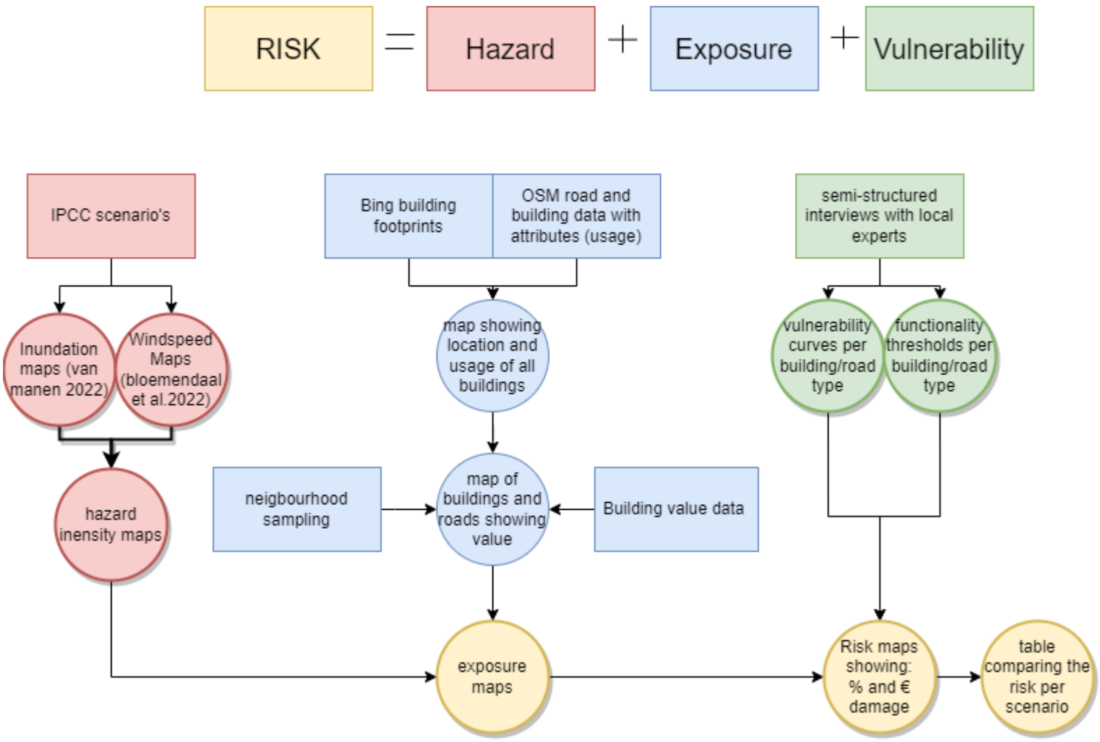


Figure 1 Schematic overview of the methods

2.1 Data collection

This research uses three types of data collection: open-source data collection, semi-structured interviews with experts, and neighbourhood sampling. Open-source data showing worldwide building footprints by Bing maps is used to show the location of all the buildings on Bonaire. Furthermore, OpenStreetMap (OSM) data is used to supplement these footprints further and add the road network to the exposure maps (Microsoft Bing Maps, 2022; OSM: OpenStreetMap, n.d.). Additionally, OSM provides the occupation of different types of buildings, which is used to value buildings.

Semi-structured interviews are held with multiple parties on the island, such as construction companies and local first responders, to gather information or to check if data values are correct and not outdated. Semi-structured interviews are chosen because they provide a versatile and flexible way to communicate and gather information (Kallio *et al.*, 2016). Its main advantage is that it gathers more detailed information by enabling researchers to find reciprocity between interviewer and participant and improvise follow-up questions based on participant's responses (Hardon *et al.* 2004). The questions are established prior to the interview and formulated using an interview question list per participant to cover all the topics.

Additionally, local fieldwork in the form of sampling per neighbourhood is needed, as no detailed information is available. The neighbourhood sampling method is a new method used for the first time in this study. It consists of gathering local information through fieldwork and determining the average building type of each specific neighbourhood based on the researchers' observations. As not all buildings on Bonaire are inside an official neighbourhood, extra neighbourhoods are created based on landmarks and OSM maps that show where houses are grouped. An overview of the neighbourhoods can be found in Annex B. Per neighbourhood, the most representative type of building is found and a geotagged panorama photo is taken of it. Based on this panorama photo and the observations at location, the average building value, building height, roof material, and roof shape are added to the neighbourhood polygon in a Geographic Information System (GIS) program. The analysis of this data will be explained in the next sections.

2.2 Hazard

2.2.1 Flood hazard

Hazard data is provided through Dullaart & Van Manen (2022). Dullaart & van Manen's study applied the SFINCS model to model sea level rise, storm surges, and waves for three time intervals (2050, 2100, and 2150) using four IPCC 2021 scenarios (SSP1-1.9, SSP2-4.5, SSP5-8.5 and SSP5-8.5 LC) (IPCC, 2021; Dullaart & van Manen, 2022). The SFINCS model uses a 30-metre resolution global elevation map, in which forests and buildings are removed. Using this global elevation map, Dullaart & Van Manen (2022) produced flood intensity maps for coastal flood hazards with a return period of once every 100 years. It must be noted, however, that inaccuracy in the elevation precision of the applied DEM is noticed, indicating a potential average overestimation of the elevation of 1,2 metres (Dullaart & van Manen *et al.*, 2022). Please see the study by Dullaart & Van Manen *et al.* (2022) for a more elaborate discussion on the implications of the chosen DEM.

2.2.2 Wind hazard

For the wind damage, future wind data of Bloemendaal *et al.* (2022) is used. They have calculated changes in tropical cyclone frequency and intensity based on past tropical storm data from 1980 to 2017. Although their results show a relative increase in the frequency of intense tropical storms for the Caribbean region, only a negligible change in maximum wind speeds was found (ibid). The data from four models, CMCC-CM2-VHR4, CNRM-CM6-1-H, EC-Earth3P-HR, and HadGEM3-GC31-HM, are averaged into one expected wind speed, which is projected over the island. Moreover, current wind speed values are compared across various scenarios to compare the difference in the expected associated future damages due to high wind speeds.

2.3 Exposure

2.3.1 Occupation and location

To find the location of all exposed assets, open-source data by Microsoft is used in combination with OSM data (Microsoft Bing Maps, 2022, OSM; OpenStreetMap, 2022). First, all building polygons for Bonaire are downloaded from OSM and categorised based on occupation. An overview of the classifications can be found in Annex C. For some buildings, OSM already provides the occupation. However, for others, we identified them ourselves based on the name of the building or company. If these are both unavailable, it is assumed that a building is residential. These residential buildings are divided into four categories based on their potential monetary value: moderate, medium, high, and high+. Each building is categorised based on the earlier described neighbourhood sampling method, resulting in an average category per neighbourhood. These averages per neighbourhood are geographically overlayed to give each residential asset a subcategory, as provided in Annex D. There is also a separate category called sheds. Sheds are selected based on their area being smaller than 50m2, as it is assumed that buildings this small are sheds next to a building or small storage units constructed of less valuable construction materials.

In case of overlap between Bing Maps and OSM, the Bing Maps data on building footprints is preferred, as it is more detailed and complete. In addition, attribute data from the OSM, such as occupation, will be transferred to the Bing Maps building footprints using spatial overlay. If there is no overlap, the nearest available OSM datapoint is taken to provide attributes and the building polygons from OSM are added to the Bing Maps database.

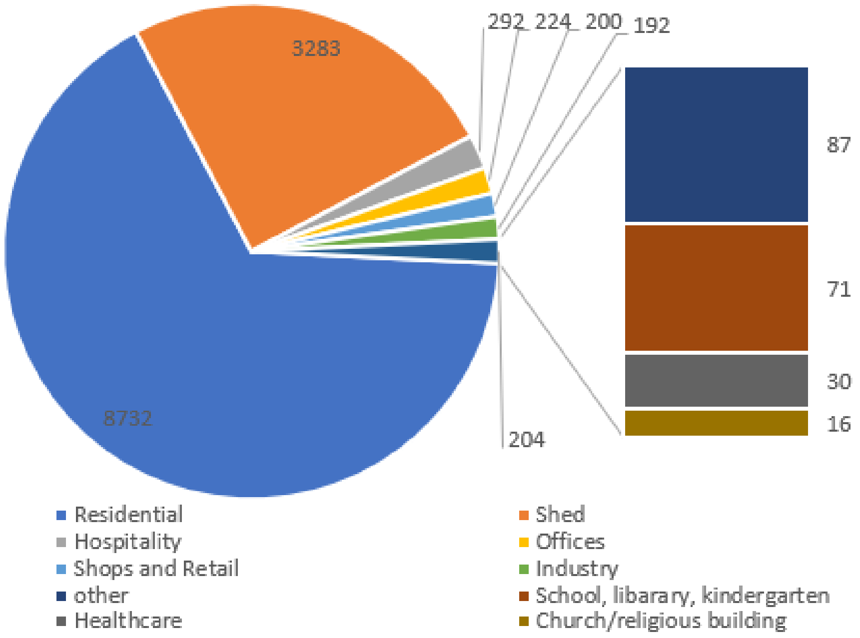


Figure 2 Distribution of categorised buildings on Bonaire

Figure 3 shows that more than 12.000 of the 13.127 identified buildings on Bonaire are residential or sheds, followed by 292 hospitality buildings and 224 office buildings. Most of the residential and shed buildings are located in or around Kralendijk and Rincon, as these are the two main cities on Bonaire. Hospitality services, such as hotels and restaurants, are mainly located close to Kralendijk or along the western coastline. The 192 industry buildings on Bonaire are mostly located in less habituated locations, such as on the south of the island, where the salt marshes and salt industry are located. Other examples of industrial buildings in less habituated locations are the BOPEC oil depots and powerplant located far north of the island.

Figure 3 indicates that there is a clear difference between the number of buildings and the total value per category. Hospitality and industry, for example, represent a higher total value than sheds, while sheds are identified more frequently than other buildings. This is primarily due to the assumption that the value of sheds is significantly lower than the value of other occupations, as they are constructed from less valuable materials. In addition, all sheds are smaller than 50 square metres, whereas the majority of other buildings are much larger, resulting in a higher total value.

2.3.2 Value

Identifying and valuing buildings is essential for estimating losses from hazards (FEMA, 2009). Similar to Huizinga *et al.* (2017), this research gives its buildings and network assets a maximum damage value based on construction cost. This is because construction costs typically refer to replacing the structural and non-structural components (Engelhardt *et al.*, 2019). Therefore, they are used in calculating direct costs or damages due to climate hazards. Determining the construction cost of each asset is done by first categorising each building on its occupation, as each occupation requires different construction elements and costs. Then, subcategories are made for each category type, so each can be given an individual construction value. The subcategories are presented in Annex D.

The value of each sub-categorized building type is based on one of three sources. For most building categories, the Rider Levett Bucknall (RLB, 2021) report provides accurate construction costs for Bonaire. If the Rider Levett Bucknall (RLB, 2021) lacks data for a category, the BCQS international (2020) report is used. For the categories "schools", "government buildings", "(movie) theatre and museums", and "religious buildings", USA data (FEMA, 2009) are used since both Rider Levett Bucknall (RLB, 2021), and BCQS (2020) do not provide data for these categories.

For residential buildings, the neighbourhood sampling method is used to determine the category of value per square metre. Neighbourhoods are classified into four categories and the individual value category can be found in Annex E. For sheds, a calculation of half the price per square metre of industrial buildings is taken, as based on fieldwork, it can be assumed that most sheds are made of similar materials as industrial buildings.

Not all of the construction expenses are derived from the same year and metric system. Therefore, all values are converted to the value per square metre for 2022 based on the Dutch Caribbean consumer price index from 2010 to 2021. (CBS, Statline, n.d.). We keep this constant for the future flood scenarios. In other words, we express the future impact of climate change into current year values.

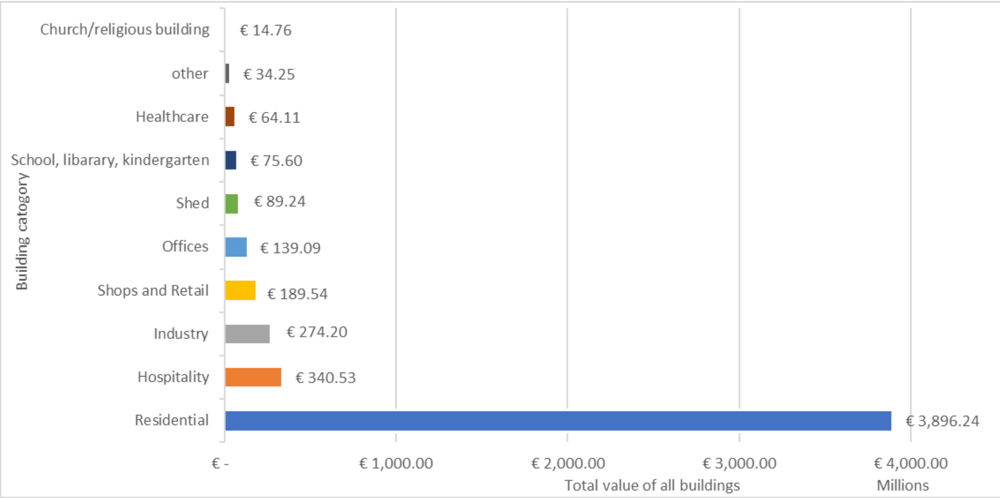


Figure 3 Distribution of total construction value per category of buildings on Bonaire

The area of each building is calculated using a GIS area calculator per polygon. Then, each building is provided with a specific value based on its area and occupation, by multiplying the area per polygon with the specific value of its category. The building polygon layer, including their newly calculated values, is combined with the hazard intensity maps for each scenario, resulting in a map showing the exact exposed elements and providing the exposed value for a hazard in 2050 and beyond.

2.3.3 Critical infrastructure

Similar to buildings, critical infrastructure is classified into different categories. These categories are developed based on the local expertise of Wolfs Company and local knowledge gained during fieldwork. They can be found in Annex C under the categories: energy, transportation, drinking water, waste, health and first responders, and industry.

Critical infrastructure services such as transportation, health, and first responders play a crucial role in preventing high casualties during and after a natural hazard. The transportation category is especially essential for Bonaire, as it includes crucial international trade facilities, such as the airport and the harbour, as well as the islands' road infrastructure network. This network is essential for people to flee from a hazard and for first responders to reach highly vulnerable locations. However, in some categories, such as energy and drinking water, only buildings are included, leaving out networks like wires and pipelines, due to the lack of local data for this study. This lack of local data forces this study to focus on critical infrastructure buildings and the road network's effectiveness in reaching buildings. As the first responders use the road network as their main transport infrastructure, this study will provide information on what areas will still be serviced by first responders and which will not. The buildings and roads that make up the infrastructure class for each category are located using OSM data and the Wolfs company's local knowledge. The plotted locations can be found in Annex F. Critical infrastructure assets are not valued since they are unknown and particularly distinctive to each type of service, making the use of generalised data illogical. However, because critical infrastructure is not valued, it is also impossible to estimate damages to these structures in terms of money. As a result, this study will only highlight the structures affected by flooding and windstorms.

2.4 Vulnerability

To identify the vulnerability per asset, a classification is made based on building height. The classifications are split into single-story or multiple-story buildings. The buildings are classified using the earlier described neighbourhood sampling, as no detailed data was available. Next, a vulnerability curve is created for each category; one for the coastal flood hazard (Figure 4) and one for the storm hazard (Figure 5). A vulnerability curve shows how much an asset or network feature will be damaged by a specific hazard of a certain intensity.

The flood vulnerability and storm vulnerability curves are constructed based on semi-structured interviews with the Independent Expertise Bureau (IEB), a consultancy bureau concerned with the insurance of buildings on Sint Maarten against natural hazards, since buildings on Sint Maarten and Bonaire have similar qualities, materials, and styles local and experts on the vulnerability of buildings on Bonaire were unavailable.

2.4.1 Flood vulnerability

A distinction is made between the single-story and the multiple-story building because single-story buildings are completely flooded at a lower level than multiple-story buildings. No distinction was made between buildings with two or more stories, as field research revealed that the majority of Bonaire's structures are no higher than two stories.

Buildings on Bonaire are all constructed in similar styles and with similar materials (Independent Expertise Bureau, personal communication, April, 2022). However, there are some differences in building quality. According to Steenbouw B.V. (2022), differences in building quality are primarily based on the size of the available budget and the age of the building. Old buildings on Bonaire used to be constructed of coral stone blocks, while buildings nowadays are made of newer, higher-quality materials. Unfortunately, all buildings are far from waterproof, making them vulnerable to coastal flood events (Steen Bouwadvies B.V., personal communication, April, 2022). The first metre of a building is especially vulnerable to flooding and water damage, making the vulnerability curves presented in Figure 2 the steepest in the first metre. This is because buildings on Bonaire are built on an approximately 30 cm thick foundation layer made of multiple layers of brick or concrete-filled diabase. Diabase is a mix of fine sand, pebbles, and soils excavated in the eastern parts of Bonaire. If the foundation, especially the diabase, gets wet, it will start to settle and cause subsidence of the walls and the foundation itself (Steen Bouwadvies B.V., personal communication, April, 2022). Moreover, the most vulnerable and valuable assets in a building, such as electrical outlets and computers, are usually placed within the first metre above the floor (Independent Expertise Bureau, personal communication, 2022). Due to the location of these vulnerable and valuable assets, the vulnerability curve (Figure 2) is steepest in the first metre for both single-story and multi-story buildings. For buildings with multiple stories, the same logic is applied. As a flood crosses the first floor, it again will hit the most valuable and vulnerable assets in the first metre above the floor. Consequently, there is a second steeper increase of damage at 3 metres. In these vulnerability curves, no distinction in usage of the buildings is made, as all buildings are constructed in a similar style and with similar materials (Independent Expertise Bureau, personal communication, 2022; Steen Bouwadvies B.V., personal communication, April, 2022).

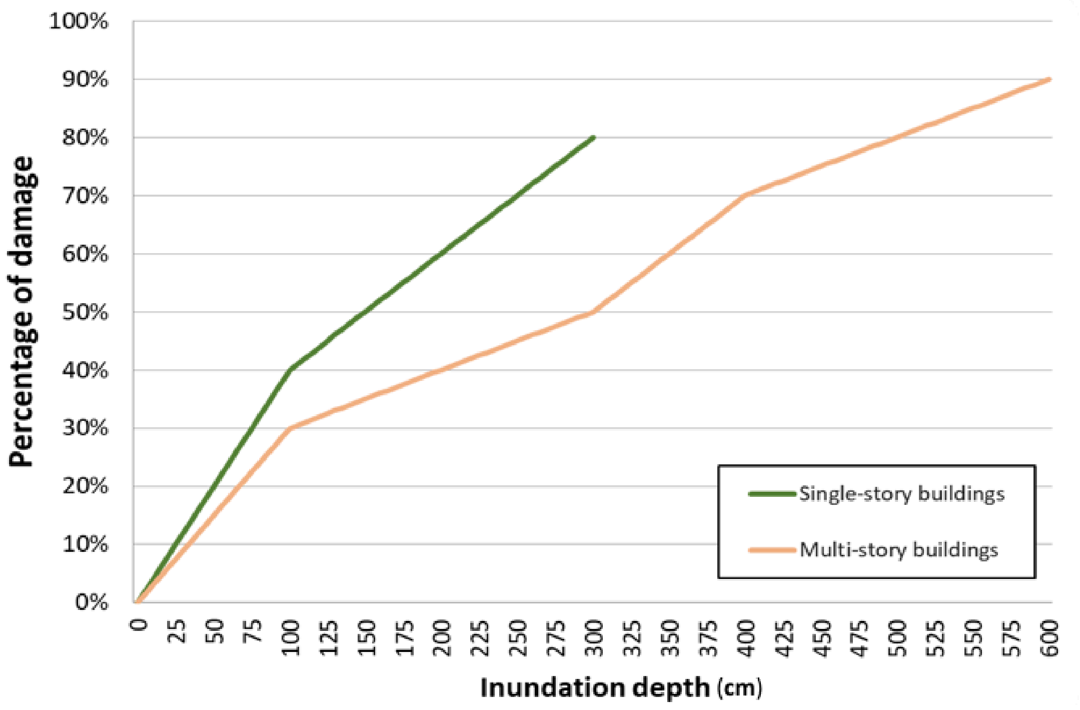


Figure 4 Flood vulnerability curve for buildings on Bonaire, for both single-story and multi-story buildings

2.4.2 Windstorm vulnerability

For the storm vulnerability curves, no distinction between building characteristics is made. According to the Independent Expertise Bureau (IEB, personal communication, April, 2022), there is no difference in vulnerability based on building quality or height, but only on the quality of the roof construction. However, no data on the quality of the roof construction is available. Therefore, together with IEB, a general building vulnerability curve is created (see Figure 5). As a general vulnerability curve is hard to construct with high accuracy, a vulnerability curve (Figure 5) with a maximum and minimum range of damage per hurricane category is made.

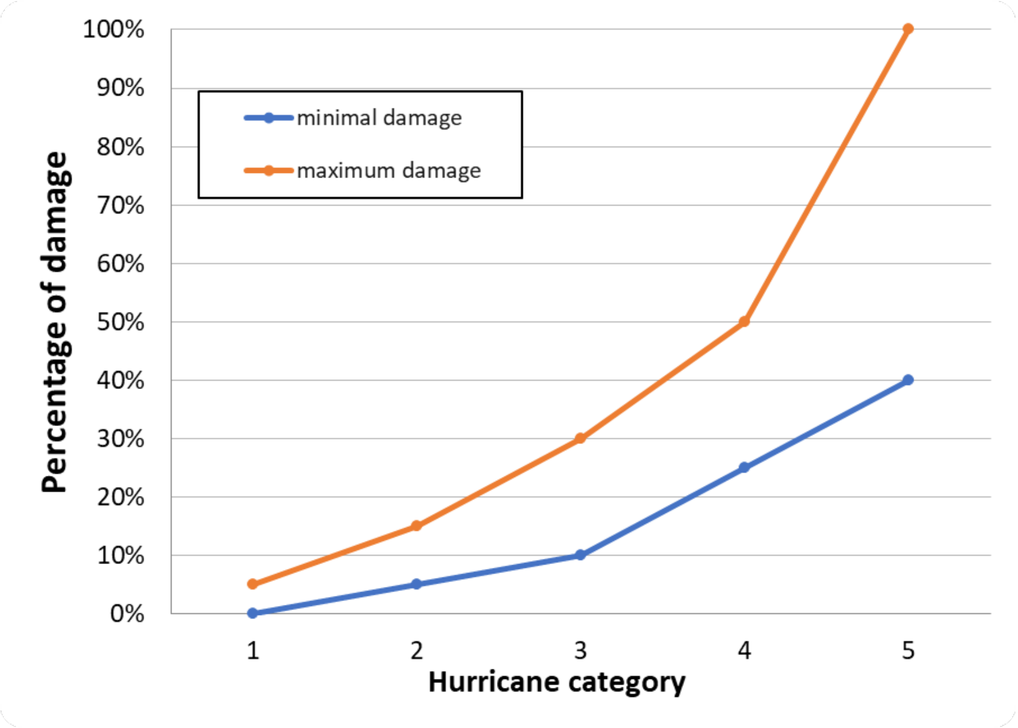


Figure 5 Windstorm vulnerability curve for buildings on Bonaire

2.4.3 Critical infrastructure vulnerability

The network analysis aims to shed light on which components of Bonaire's road network will sustain damage and which portions of Bonaire will not have access to that network's services. However, due to the lack of publicly accessible local knowledge, a vulnerability curve or functionality threshold per infrastructure category cannot be constructed for Bonaire. For example, no exact data on buildings' vulnerability to floods and high wind speeds is available. It is stated by local first responders that both the hospital and the fire station are built to be natural disaster-proof, meaning they can withstand high wind speeds and flood levels (Fire fighter, personal communication, May, 2022). It is furthermore assumed that the harbour construction is designed to be strongly resistant to flood damage.

As explained in the previous exposure section, there is no local knowledge available on networks such as pipelines and powerlines, but only on roads. This makes it impossible for this research to construct a vulnerability curve or functionality threshold for these networks except for road infrastructure. A functionality threshold of 40 cm for the examined road infrastructure network is constructed based on semi-structured interviews with local experts. Roads that are 40 cm or more underwater are assumed to be non-functional for any vehicle, as this is the maximum flood height for local first responder vehicles to drive through (IEB, personal communication, May, 2022). The identification of non-functional roads due to flooding is made by spatially overlapping the flood maps with the road infrastructure maps.

In addition to the direct damages to critical infrastructure, this study evaluates the road network's connectivity. Roads that are cut off from the network are added to the already unusable roads as they are unreachable and therefore also unusable. Which roads will be cut-off is determined using a line polygon connectivity checking tool in a GIS. This tool shows what parts of the original network are cut-off once the flooded parts are out of the network. The combination of the flooded and disconnected roads is evaluated in terms of connectivity with critical infrastructure buildings. This shows to which areas these buildings can still provide services. The main focus is on whether first responders are still able to reach residential areas and other critical infrastructure buildings so that they can provide aid and minimise damage when hazards hit.

3 Results

The results section will only present damages as a result of coastal flooding, as our approach did not find damages related to wind (we elaborate on this in Chapter 4).

3.1 Impact and damage to buildings due to storm inundation

Figure 6 visualises current buildings on Bonaire and inundation levels in four different climate scenarios (SSP 1-, SSP 2-4.5, SSP 5-8.5 and SSP5-8.5 LC) for 2050 and 2150. It is shown that the greatest flood risk will be in the south and along the coast of Bonaire, which is already affected in 2050 in a SSP 1-1.9 climate projection. Although the difference in inundation depth appears to be relatively small for the three climate scenarios in 2050, more prominent differences can be seen for the climate projections in 2150. Note that, as described in section 2.2.1 (Hazard), inaccuracy in the applied DEM is identified, which may result in an underestimation of inundation levels and associated damages.

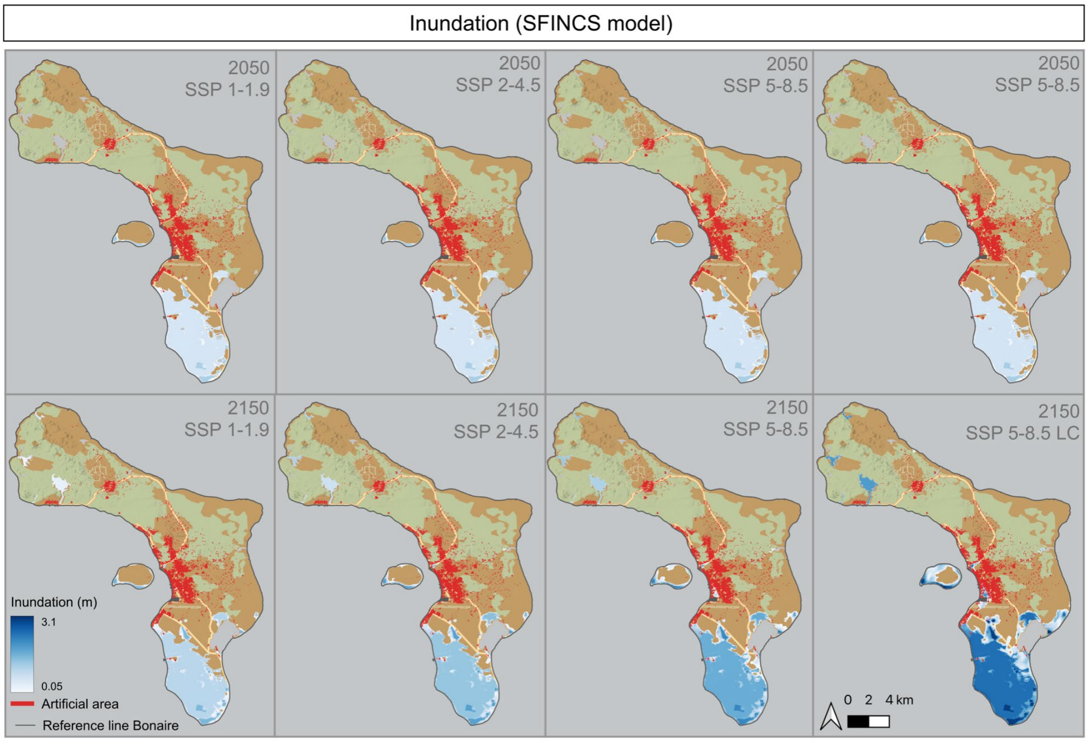


Figure 6 Comparison of hazard extent for each climate scenarios SSP 1-1.9, SSP 2-4.5, SSP 5-8.5 and SSP5-8.5 LC in 2050 and 2150

3.1.1 Impact and building damage costs in 2050

As presented in Table 1, the differences in monetary impacts of flood hazards across the various climate scenarios for 2050 are relatively small: expected damage values associated with climate scenario SSP 5-8.5 LC are estimated to be almost 4,4% higher than the expected costs related to climate scenario SSP 1-1.9. This is due to the fact that the flood risk does not affect more buildings in the most extreme climate scenario than in the least extreme climate scenario. On Bonaire, only few buildings are located directly on the (southern) coast, since building along coastlines is prohibited, with few exceptions (Steen Bouwadvies B.V., personal communication, April, 2022). Although the number of buildings hit remains the same in the different climate projections, namely 54, the damage costs are expected to increase due to higher levels of inundation, which can cause additional damage to the houses hit. The difference in total damage between SSP 1-1.9 and SSP 5-8.5 LC is approximately 600.000 USD.

Table 1 Overview of the effects of climate scenarios SSP 1-1.9, SSP 2-4.5, SSP 5-8.5 and SSP5-8.5 LC in 2050 and 2150

Scenario	Year	Number of buildings hit (#)	Average inundation of affected buildings (m)	Total damage (USDm)
SSP 1-1.9	2050	54	0.340	13.8
	2150	100	0.400	23.1
SSP 2-4.5	2050	54	0.350	14.1
	2150	142	0.508	38.4
SSP 5-8.5	2050	54	0.361	14.3
	2150	471	0.385	76.2
SSP 5-8.5 LC	2050	54	0.365	14.4
	2150	1655	0.533	316.8

Figure 7 indicates that in the SSP 1-1.9 scenario for the year 2050, 21 of the 54 exposed buildings to storm inundation are located in the neighbourhood of Belnem, which is significantly more compared to the other neighbourhoods, resulting in $2.19 million of the total damage of 13.8 USDm. In 2150, Belnem will be even more severely damaged, as an additional 87 buildings will be damaged due to coastal flooding, resulting in estimated total damage costs of 23.1 USDm. The estimation that (at least) 100 out of the 882 (8.82%) buildings in Belnem will be hit in 2150, even in the least severe climate scenario, suggests that local flooding can cause significant property damage within a specific neighbourhood and will result in severe local impact, which can be disruptive for a whole neighbourhood on Bonaire. The damages found in Belnem demonstrate that, in order to prevent the damage and disruption caused by climate change, neighbourhoods along the coast, which are generally the most valuable, must be protected against flooding by 2050.

As described extensively in Dullaart & van Manen *et al.* (2022), sea level rise may also cause permanent inundation on some parts of the island. While it is difficult to disentangle the potential damage between storm surge inundation and permanent inundation, it should be noted that the effects of storm surge inundation alone may underestimate the potential total damages. As a result of permanent inundation, one can expect that buildings cannot be used anymore. This would indicate much higher damages as a result of permanent abandonment of certain buildings. The number of buildings that could be affected by permanent inundation is provided in Annex J. The results show that only three buildings might be affected by permanent inundation in the year 2050, across all scenarios (compared to the 54 houses that could be affected by storm surge inundation). However, this could substantially increase towards 2150. In the case of SSP1-1.9, this could increase to up to 48 buildings. For SSP5-8.5, this number could increase to 185 buildings by the year 2150.

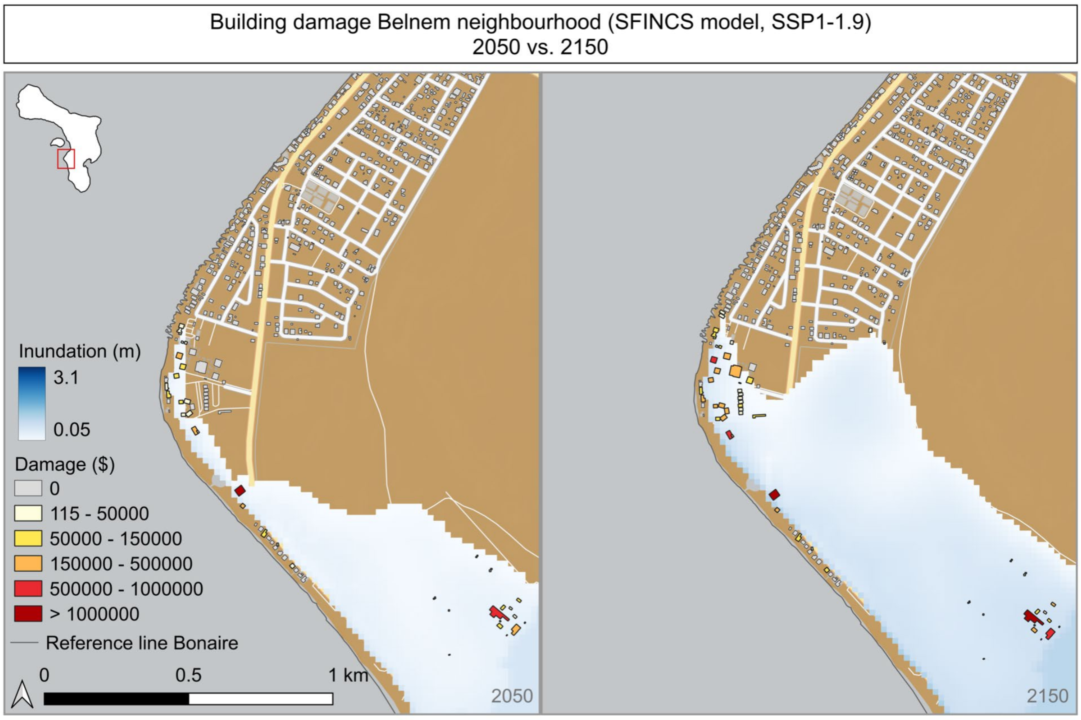


Figure 7 *Damage of buildings (%) in the neighbourhood of Belnem – climate scenario SSP 1-1.9 in 2050 and 2150*

3.1.2 Impact and damage costs in 2150

When extending the time factor to 2150 for each scenario, much more prominent impacts associated with the different climate projections can be seen and the extent and intensity of the flood hazard increase. In general, there is an increase in average flood depth, and the hazard's extent may also substantially increase in 2150 compared to 2050. While the average inundation (in metres) increases in climate scenario SSP 2-4.5 compared to SSP 1-1.9, the average inundation is lower in SSP 5-8.5 (Table 1). This can be explained by the fact that the inundated area (metres) increases more than the increase in SLR (metres), which results in a lower average inundation level.

The enlarged inundated area translates into higher flood damage costs, as indicated in Table 1. However, it must be noted that estimating the exposure value for 2150 is sensitive and complex: the location of (future) buildings and the current inflation cannot be extrapolated to 2150, due to a lack of extensive data on inflation rates and uncertainty about the locations and quantity of buildings. However, it can be assumed that the city of Kralendijk and other buildings will not be (completely) moved to another geographic location. Based on these assumptions, the damage costs associated with the different climate scenarios have been estimated for 2150. Table 1 indicates that whereas expected damages in 2050 SSP 1-1.9 account for 13.95 USDm, these costs are expected to be tripled in the SSP 5-8.5 scenario (75.24 USDm).

When zooming in on Kralendijk, we find no buildings to be impacted in 2050 in any of the climate scenarios. In 2150, however, parts of the current Kralendijk may be flooded in case of a coastal flood hazard for the SSP scenarios 5-8.5 and 5-8.5 LC. Figure 8 shows a comparison of the building damage caused by a flood in 2150 under the climate scenario SSP1-1.9 versus SSP5-8.5 LC. While the centre does not flood under the SSP1-1.9 conditions, severe building damages in the city centre of Kralendijk and the airport are predicted under the conditions of climate scenario SSP5-8.5 LC.

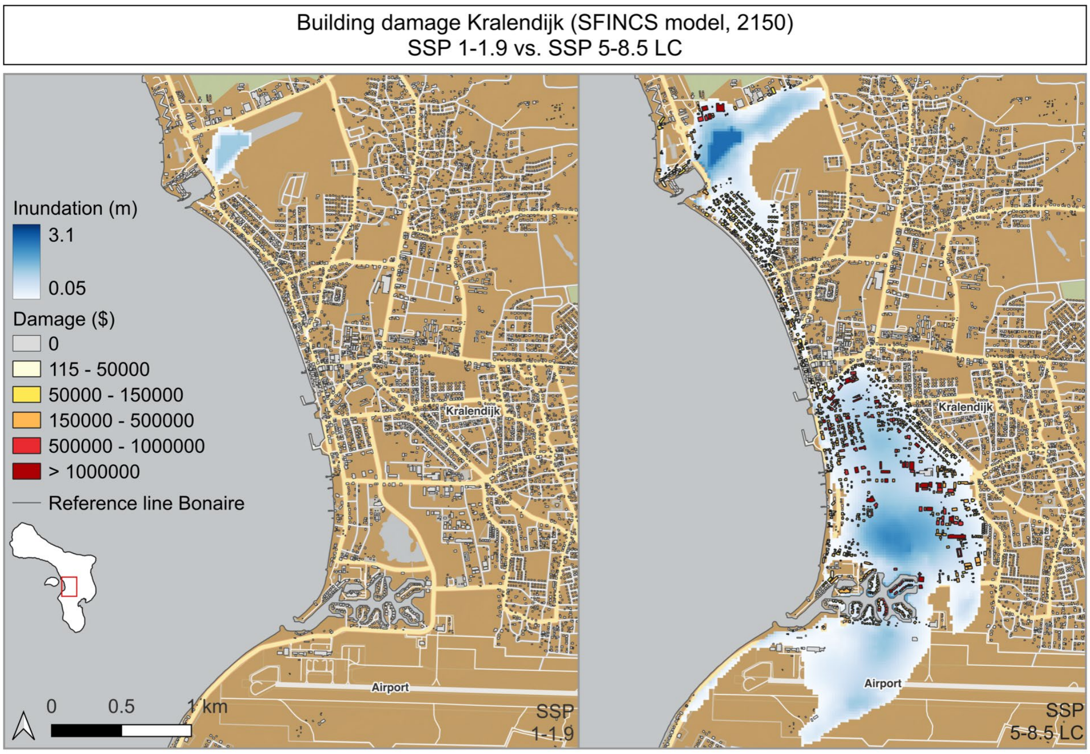


Figure 8 Damage of buildings (%) in Kralendijk – climate scenarios SSP 1-1.9 and SSP 5-8.5 LC in 2150

3.2 Impact on critical infrastructure

Figure 9 illustrates Bonaire's key infrastructure, such as essential buildings and roadways, in 2050 in two climate projections (SSP 1-1.9 and SSP 5-8.5 LC). All of Bonaire's essential infrastructure vulnerable to climate-driven flood risks is located in the south and/or along the coast. According to local firefighters, it can be presumed that roads are still passable until they are flooded to a depth of 40 centimetres, as this is the largest depth through which a first responders vehicle can still travel (Fire fighter, personal communication, May, 2022). When considering the impact on infrastructure such as roadways, even roads that are not immediately exposed to flood threats can be severed from the network, rendering the entire road inoperable. As shown in Figure 9, all roads in the Southern part of Bonaire will be unusable in 2050 under both climate scenarios (SSP 1-1.9 and SSP 5-8.5 LC). Therefore, emergency services cannot reach the Cargill facilities and other buildings in these areas of Bonaire. Please refer to the research by van Beukering *et al.*, 2022 for a more elaborate discussion on the impacts on tangible cultural heritage.

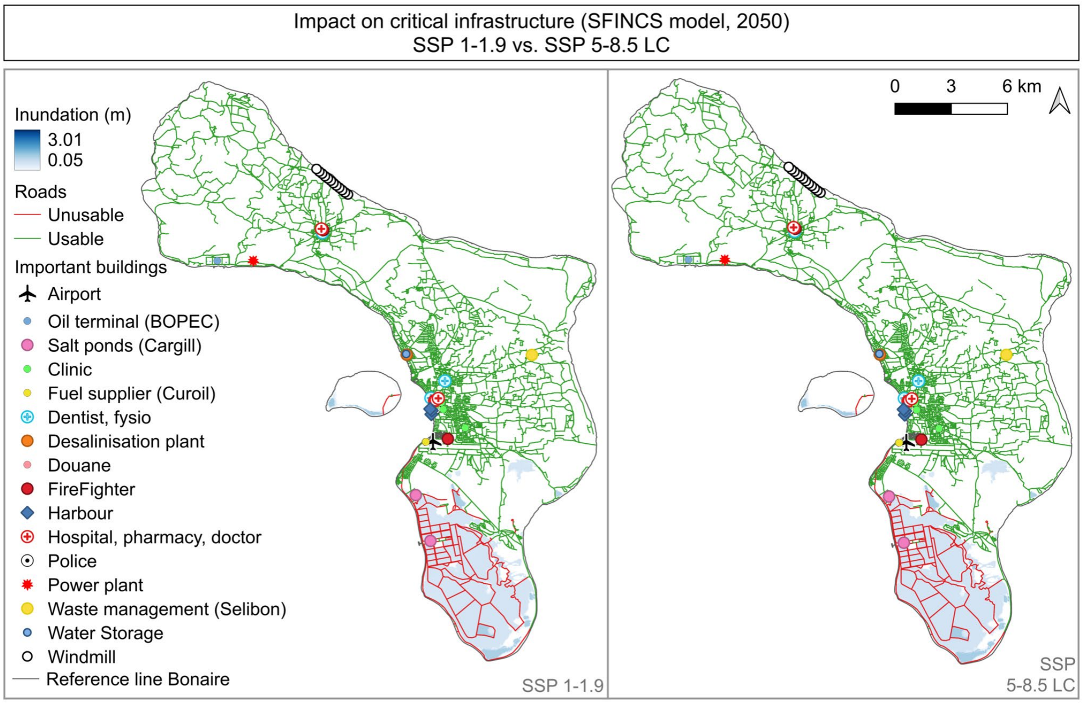


Figure 9 Impact on critical infrastructure on Bonaire - climate scenarios SSP 1-1.9 and SSP 5-8.5 LC in 2050

When looking at the inundation impacts in 2150, similar to the impacts on buildings, the change in time interval results in more severe impacts to critical infrastructure. Figure 10 indicates that not only the infrastructure in the Southern part of Bonaire is impacted, but under climate scenario SSP 1-1.9, the road to BOPEC and powerplant in the northern part of Bonaire is also unpassable. When zooming in on BOPEC, it can be seen that the facilities themselves are not hit by any hazard (Annex H). Furthermore, it is notable that the harbour is expected to be hit by the flood hazard in any scenario in 2150. However, this is a structure built into the water and made to embrace the impacts of strong waves and water height changes. Therefore, it is expected that damage to these structures will be minimal. Furthermore, Figure 10 shows that projections for climate scenario SSP 5-8.5 LC in 2150 indicate that the road to waste management facility Selibon will be unpassable through the direct road, but not completely cut off from the road network or hit by a coastal flood hazard.

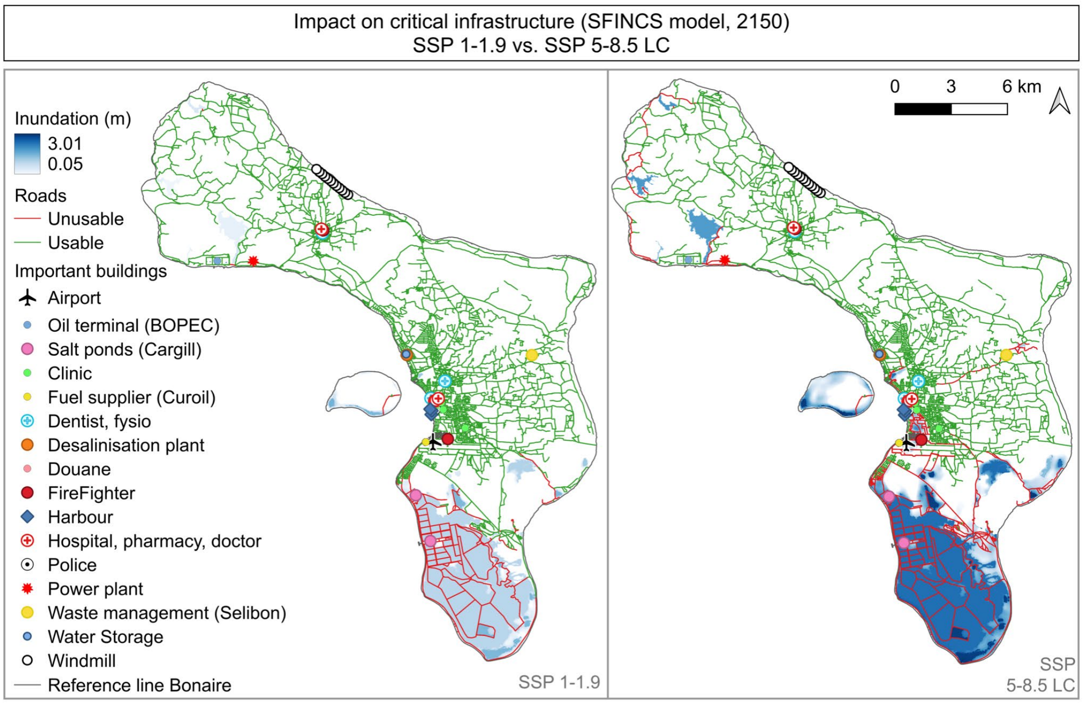


Figure 10 Impact on critical infrastructure on Bonaire - climate scenarios SSP 1-1.9 and SSP 5-8.5 LC in 2150

4 Discussion

Global research suggests that SIDS worldwide would suffer from higher levels of vulnerability to climate change due to their smallness, remoteness, and exposure to natural hazards (Scandurra *et al.*, 2018). Especially due to global warming and the increase of surface temperatures, it is expected that only 60,000 of all the people living on SIDS will be spared an inundation event globally by the year 2150 (IPCC, 2021; Rasmussen *et al.*, 2018). Furthermore, recent research showed that sea level rise on Bonaire would be faster than the world average (Le Bars *et al.*, 2022). This may lead to more extensive and frequent flooding, possibly more storm hazards, and high numbers of exposed buildings. The results in the current study also find that various buildings are exposed to coastal flooding hazards, with varying impacts depending on the applied climate projection and time interval. In addition, by 2050, numerous coastal and southern roads on the island will be unusable, even under climate scenario SSP 1-1.9, making it impossible for emergency services to reach these areas and the buildings that are located there. In 2150, the oil terminal in the north of Bonaire will also be inaccessible due to an impassable road. In terms of building damage, it is anticipated that 54 buildings in the southern region of Bonaire will be affected in 2050. In the year 2150, the number of damaged buildings ranges from 108 (SSP 1-1.9) to 471 (SSP 5-8.5 LC), resulting in estimated damages of 25 USDm and 316.8 USDm, respectively. Since the majority of affected structures are located in the southern region of Bonaire and the Belnem neighbourhood in particular, flooding hazards can have severe local effects and disrupt an entire Bonairian neighbourhood. In 2150, under certain climate scenarios Kralendijk is predicted to flood, which will also have severe consequences. The Dutch government and local authorities should implement coastal adaptation measures to protect at-risk communities from coastal flooding hazards.

4.1 Limitations

Although this study provides useful insights for policymakers on infrastructure location and the potential effects of coastal flooding on this infrastructure, it comes with various uncertainties and limitations. One of the problems inherent with studies on disaster risk modelling on this small scale and location is the number of assumptions required to make in such a data-scarce analysis. This is not only the case for the assumptions taken in the analysis of this study but also for the approaches taken in developing the external input data being used. In this research, this includes the hazard intensity maps and the building exposure data.

4.1.1 Digital Elevation Model

As stated by Koks *et al.* (2019), flood risk analysis reliability depends on the uncertainty of the hazard side of the risk equation and especially the digital elevation map (DEM). Vousdoukas *et al.* (2018) showed that a change in resolution from 10 to 100 metres could change the estimated EAD by 200%. The hazard intensity maps used in this research are constructed for a hazard with a return period of 1-100 years using a global 30 metres resolution DEM for the year 2050. As described by Dullaart & van Manen (2022), the DEM applied in this study appeared to differ significantly from Dullaart &

van Manen’s (2022) self-measured elevation points and those from Geomaat Bonaire (geodetic engineering company), with an average overestimation of the elevation of 1,2 metres. In case a correction of the average inaccuracy of the DEM would be applied to the DEM of Bonaire as a whole, the number of buildings hit, and associated damage value would significantly increase and Kralendijk would be flooded in 2050 climate scenario SSP 1-2.6 (Annex I). The number of buildings hit would range from 181 to 1831 buildings, resulting in a total damage value of approximately 36 and 207 USDm for climate scenarios SSP 1-2.6 in 2050 and SSP 5-8.5 in 2150, respectively.

4.1.2 Building value

In addition, recent research demonstrates that the value of elements exposed and the depth-damage curves utilised are the most influential factors in the estimation of flood damage (de Moel & Aerts, 2010). In this study, the value of the exposed elements is determined using recent, specific, expert-verified, and as locally relevant data as possible.

For the island of Bonaire, availability of data on buildings and their values is scarce. This study attempts to overcome significant uncertainties in the value of exposed elements by verifying building-level data for each neighbourhood. This allows for a greater level of specificity regarding the value and vulnerability of residential buildings. As residential buildings make up more than half of all buildings on Bonaire, it was attempted to reduce uncertainty through ground-truthing our data during a local field trip. As per-neighbourhood averages can lead to overgeneralization, uncertainty in the estimates may remain unavoidable. Nevertheless, the methodology creates a more accurate representation of the value and height of buildings than the assumption that all residential buildings are of equal value. This innovative methodology can be used in similar data-scarce locations as long as fieldwork and classifications can be performed.

Compared to the number of categories on the value of assets, the vulnerability curves provided are relatively general. This generalisation is not considered a significant uncertainty, as local fieldwork and expert interviews showed that buildings on Bonaire are all constructed with similar materials and styles (Annex H), thereby limiting variation in asset values. More extensive and detailed data on roof construction quality and wind speed vulnerability would, however, create a higher level of detail. Currently, this data is unavailable.

Due to the difficulty to assess the building values of houses, we were not able to properly quantify the economic impacts to Bonaire due to permanent inundation. As such, the damage estimates provided in this report could be interpreted as a lower bound estimate of the impacts of climate change.

4.1.3 Critical infrastructure networks

Due to the limited availability of data on Bonaire's critical infrastructure, particularly for critical infrastructure networks, it was not feasible to provide a complete overview of the effects of climate-related hazards on all infrastructural networks. Therefore, the scope of this study is limited to an evaluation of the vulnerability of roads and critical infrastructure assets. However, the methods applied to analyse the road infrastructure are readily and easily applicable to other networks that are currently unavailable. For this research to become more comprehensive on the impacts of climate hazards to critical infrastructure, additional information is needed on the functionality thresholds/vulnerability curves and the location of other networks, such as the electricity network and sewage. This study provides a zoom-in on the most critical cut-off locations, such as oil terminal BOPEC and the powerplant, which shows the necessity of the availability of a functional road network.

4.2 Next steps

4.2.1 Future research

Taking the previous limitations of this study into consideration, future research should focus on: (1) the formation of vulnerability curves for high wind speeds lower than category one and multiple types of buildings, since more detailed vulnerability curves per building type will provide a more detailed and precise risk calculation; (2) identifying the location and vulnerability of other critical infrastructure networks such as electricity and sewage, so that a more complete picture of the risk to critical infrastructures can be created, and; (4) determining the vulnerability of other critical infrastructure networks, such as electricity and sewage, so that a more comprehensive risk assessment can be performed. By examining these components, a more complete local view of the expected damages for each scenario period can be generated. In addition, a more accurate DEM should be developed for Bonaire to gain a better understanding of the inundation depth. Also, if additional flood hazard maps were created for multiple return periods, annual damages could be estimated. These anticipated annual damages would provide a solid basis for comparing the costs of various adaptation measures.

4.2.2 Adaptation measures

Given that coastal flooding due to climate change will cause damage to Bonaire in multiple ways, and that considering that the inaccuracy of the DEM will most likely underestimate the expected damages, Bonaire should start developing appropriate adaptation strategies. There is a particular need for national governments and other actors to focus on: (1) the protection of the southern part of Bonaire before 2050, such as Belnem and the salt ponds, as this is highly vulnerable to flooding; (2) the protection of Kralendijk before 2150 because it will partially flood in the different climate projections; (3) the protection of roads in order to ensure that critical infrastructure assets, such as oil terminal BOPEC, are always reachable by emergency services and workers. A one-size-fits-all solution is inapplicable, as each focus area is located differently and faces diverging threats, resulting in the need for unique adaptation techniques. There are various types of adaptation measures that could be implemented. Buijs *et al.* (2022) found that nature-based solutions seem to be favourable.

Mangroves could be one of the nature-based adaptation techniques that could reduce flood risk on Bonaire. They are currently only located in the eastern part of Bonaire, at the Lac Bay, where they provide both nature and reduce flood risk. Mangroves not only reduce flood risk for low-elevation coastal zones but are also sustainable and costeffective alternatives (Hochard *et al.*, 2019; Menéndez *et al.*, 2020; Gijsman *et al.*, 2021). Furthermore, mangroves, in contrast to hard flood protection infrastructures, recover in and adapt to a changing climate making them more suitable for reducing climate change-driven flood hazards. However, mangroves may collapse when climatic changes exceed thresholds, making them less reliable and possibly not applicable for all locations on Bonaire (Gijsman *et al.*, 2021). Additionally, the construction of new mangroves reduces the accessibility of the sea, resulting in fewer locations for shore diving, which is crucial to Bonaire's economy and tourism.

Other options could be placing hard adaptation measures such as a sea wall. However, sea walls and other hard coastal flood adaptation measures are controversial. Moreover, in case they are poorly designed and constructed, they can lead to an increase rather than a decrease in erosion and often not a reduction in flood prevention (Betzold & Mohamed, 2016). For a complete overview of the trade-offs of different coastal flooding adaptation measures on Bonaire, please consult the study by Tiggeloven *et al.* (2022).

5 Conclusion

This study has identified to what extent Bonaire's buildings and critical infrastructure will be directly impacted by future climate change in 2050, focusing on floods and storms. This study has presented a new approach for calculating the exposure and vulnerability by categorising residential buildings on their construction value and height, called neighbourhood sampling. These methods result in detailed risk analysis for the data-scarred area of Bonaire.

Our results show that Bonaire will most likely be partially exposed to a once in a 100 year flood hazard in 2050. We find that the estimated exposed buildings are 54 in 2050, most of which are residential buildings along the southern coastline. The 54 exposed buildings face a total financial risk of approximately 19,7 USDm. However, due to the accuracy of the applied DEM, the results are assumed to be an underestimation of the real total building damage value.

The constructed vulnerability curves are a generalisation for all building types, whereas the valuation of buildings uses a more precise categorization. The network analysis shows that for 2050 no major risk will occur due to both flooding and storms. However, depending on the scenario, a higher level of risk can be expected in the year 2150. As a result, this study recommends that future research should focus on the risk function's hazard element and the construction of more detailed vulnerability curves to obtain more knowledge and data for performing a more precise risk analysis.

The analysis conducted under this study demonstrates that: (1) climate-driven flood hazards with a return period of once every hundred years in 2050 will lead to flooding of the southern salt flats and along the coast of Bonaire; (2) economic impacts and risk of flood hazards can become quite significant, depending upon the researched period and scenario, and; (3) no critical infrastructure buildings on Bonaire will be directly damaged by any of the researched hazards in 2050, although the BOPEC oil terminal and adjacent powerplant will most likely be cut off of the road network. However, a flood of the airport runway can be expected depending on the climate change scenario and temporal factors. Therefore, local governments and other actors need to be increasingly prepared for extreme flooding events, which will become more severe due to climate change and its temporal factors. By incorporating the results of this research on climate change risks into long-term planning processes, significant economic damages and possible catastrophes can be prevented.

This study contributes to a growing literature of integrating climate change projections into local risk analysis and adaptation planning. It makes a first attempt to overcome data scarcity for locations such as SIDS by introducing a new methodology to identify the value of residential buildings based on an average value per neighbourhood. Additionally, this study makes an attempt to aggregate and analyse all available critical infrastructure data of Bonaire into one research by using a simple modelling approach and local expertise to conduct vulnerability risk. Finally, the study offers a first insight into the direct damages expected due to a climate-driven increase in flood and storm hazards for Bonaire, showing which areas are most at risk and why. It provides helpful data for integrating climatic risks into long-term planning for Bonaire.

References

Adeoti, T., Fantini, C., Morgan, G., Thacker, S., Ceppi, P., Bhikhoo, N., Kumar, S., Crosskey, S., & O'Regan, N. (2020). *Infrastructure for Small Island Developing State*s. UNOPS, Copenhagen, Denmark. https://content.unops.org/publications/Infrastructure_SIDS_EN.pdf?mtime=20201013090607

Allen, T. R., Crawford, T., Montz, B., Whitehead, J., Lovelace, S., Hanks, A. D., Christensen, A. R., & Kearney, G. D. (2018). Linking Water Infrastructure, Public Health, and Sea Level Rise: Integrated Assessment of Flood Resilience in Coastal Cities. Public Works *Management & Policy, 24*(1), 110–139. https://doi.org/10.1177/1087724x18798380

Amnesty international. (2021, 12 augustus). Daphina Misiedjan: Klimaatrechtvaardigheid? Dat is er niet voor de Caribische eilanden. *Wordt Vervolgd*. accessed at 25 februari 2022, van https://www.amnesty.nl/wordt-vervolgd/daphina-misiedjan-klimaatrechtvaardigheid-caribische-eilanden

Ault, T. (2016). Island water stress. *Nature Climate Change, 6*(12), 1062–1063. https://doi.org/10.1038/nclimate3171

Bak, R. P. M., Nieuwland, G., & Meesters, E. H. (2005). Coral reef crisis in deep and shallow reefs: 30 years of constancy and change in reefs of Curaçao and Bonaire. *Coral Reefs, 24*(3), 480. https://doi.org/10.1007/s00338-005-0060-y

BCQS inernational. (2020, september). Caribbean & Latin America construction Market Trend Report. https://bcqs.com/2020/10/29/bcqs-releases-2020-caribbean-latin-america-market-trend-report/

Betzold, C., & Mohamed, I. (2016). Seawalls as a response to coastal erosion and flooding: a case study from Grande Comore, Comoros (West Indian Ocean). *Regional Environmental Change, 17*(4), 1077–1087. https://doi.org/10.1007/s10113-016-1044-x

Bloemendaal, N., de Moel, H., Martinez, A. B., Muis, S., Haigh, I. D., Van der Wiel, K., Haarsma, R. J., Ward, P. J., Roberts, M. J., Dullaart, J. C. M., & Aerts, J. C. J. H. (2022). A globally consistent local-scale assessment of future tropical cyclone risk. *Science Advances, 8*(17). https://doi.org/10.1126/sciadv.abm8438

Bueno, R., Herzfeld, C., Stanton, E. A., & Ackerman, F. (2008). *The Caribbean and climate change: the costs of inaction*. Stockholm Environment Institute, U.S. Center and Global Development and Environment Institute, Tufts University. https://pubs.iied.org/sites/default/files/pdfs/migrate/G02498.pdf

Buijs, S. (2022). *Protecting Bonaire against coastal flooding: A participatory multi-criteria analysis of coastal adaptation options* [Unpublished master's thesis]. Vrije Universiteit Amsterdam

CBS, Statline. (n.d.). Caribisch Nederland; consumentenprijsindex (CPI) 2017=100. opendata.cbs.nl. Consulted on 1 June 2022, from https://opendata.cbs.nl/#/CBS/nl/dataset/84046NED/table

Debrot, A. O., & Bugter, R. J. F. (2010). *Climate change effects on the biodiversity of the BES islands: Assessment of the possible consequences for the marine and terrestrial ecosystems of the Dutch Antilles and the options for adaptation measures*. (No. C118/10). Alterra.

Delmonaco G, Margottini C, Spizzichino D (2006) Report on new methodology for multi-risk assessment and the harmonisation of different natural risk maps. Deliverable 3.1, ARMONIA

Englhardt, J., de Moel, H., Huyck, C. K., de Ruiter, M. C., Aerts, J. C. J. H., & Ward, P. J. (2019). Enhancement of large-scale flood risk assessments using building-material-based vulnerability curves for an object-based approach in urban and rural areas. *Natural Hazards and Earth System Sciences, 19*(8), 1703–1722. https://doi.org/10.5194/nhess-19-1703-2019

EPA: United States Environmental Protection Agency. (2017, 19 januari). International Climate Impacts | Climate Change Impacts | US EPA. Www.Epa.Gov. Consulted on 25 Februari 2022, from https://19january2017snapshot.epa.gov/climate-impacts/international-climate-impacts_.html#main-content

Europees Parlement Liaisonbureau in Nederland. (n.d.). Bonaire, Saba en Sint Eustatius. European Parliament. Consulted on 25 Februari 2022, from https://www.europarl.europa.eu/thenetherlands/nl/eu-info/bonaire-saba-en-sint-eustatius

Fakhruddin, B. S., Boylan, K., Wild, A., & Robertson, R. (2020). Assessing vulnerability and risk of climate change. In Editor(s): Sillmann, J., Sippel, S., & Russo, S. (eds), *Climate Extremes and Their Implications for Impact and Risk Assessment* (pp. 217–241). Elsevier. https://doi.org/10.1016/b978-0-12-814895-2.00012-4

FEMA, Department of Homeland Security, Federal Emergency Management Agency, & Mitigation Division. (2009). Hazus, Multi-hazard Loss Estimation Methodology, Flood Model, Technical Manual (2.1). Fema, Washington, D.C. https://www.fema.gov/flood-maps/tools-resources/flood-map-products/hazus/user-technical-manuals

Foerster, E., Krien, Y., Dandoulaki, M., Priest, S., Tapsell, S., Delmonaco, G., Margottini, C., & Bonadonna, C. (2009). *Methodologies to assess vulnerability of structural systems*. Del. 1.1.1., ENSURE, http://eea.eionet.europa.eu/Public/irc/eionet-circle/airclimate/library?l=/public/2010_citiesproject/interchange/project_deliverables/ensure_del111pdf/_EN_1.0_&a=d

Garschagen, M., Hagenlocher, M., Comes, M., Sabelfeld, R., Lee, Y. J., Grunewald, L., Lanzendörfer, M., Mucke, P., Neuschäfer, O., Pott, S., Post, J., Schramm, S., Schumann-Bölsche, D., Vandemeulebroecke, B., Welle, T., & Birkmann, J. (2016). *World Risk Report 2016: The importance of infrastructure*. United Nations University Institute for Environment and Human Security. https://www.preventionweb.net/publication/world-risk-report-2016-importance-infrastructure

Gijsman, R., Horstman, E. M., Van der Wal, D., Friess, D. A., Swales, A., & Wijnberg, K. M. (2021). Nature-Based Engineering: A Review on Reducing Coastal Flood Risk With Mangroves. *Frontiers in Marine Science, 8*. https://doi.org/10.3389/fmars.2021.702412

Gunasekera, R., Ishizawa, O., Aubrecht, C., Blankespoor, B., Murray, S., Pomonis, A., & Daniell, J. (2015). Developing an adaptive global exposure model to support the generation of country disaster risk profiles. *Earth-Science Reviews, 150*, 594–608. https://doi.org/10.1016/j.earscirev.2015.08.012

Haarsma, R., Groenland, R., Stoffelen, A., Geurts, H., & KNMI. (n.d.). KNMI – Orkanen in Caribisch Nederland. knmi.nl. Consulted on 1 juni 2022, from https://www.knmi.nl/kennis-en-datacentrum/achtergrond/orkanen-in-caribisch-nederland

Hardon, A., Hodgkin, C., & Fresle, D. (2004). How to investigate the use of medicines by consumers. In *How to investigate the use of medicines by consumers* (pp. 89-89).

Hawker, L., Uhe, P., Paulo, L., Sosa, J., Savage, J., Sampson, C., & Neal, J. (2022). A 30 m global map of elevation with forests and buildings removed. *Environmental Research Letters, 17*(2), 024016. https://doi.org/10.1088/1748-9326/ac4d4f

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., & Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change, 3*(9), 816–821. https://doi.org/10.1038/nclimate1911

Hochard, J. P., Hamilton, S., & Barbier, E. B. (2019). Mangroves shelter coastal economic activity from cyclones. *Proceedings of the National Academy of Sciences, 116*(25), 12232–12237. https://doi.org/10.1073/pnas.1820067116

Huizinga, J., de Moel, H., & Szewczyk, W. (2017). *Global flood depth-damage functions: Methodology and the database with guideline*s. (No. JRC105688). Joint Research Centre (Seville site).

IPCC, 2021: *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Kallio, H., Pietilä, A. M., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing, 72*(12), 2954–2965. https://doi.org/10.1111/jan.13031

Kappes, M. S., Keiler, M., Von Elverfeldt, K., & Glade, T. (2012). Challenges of analyzing multi-hazard risk: a review. Natural Hazards, 64(2), 1925–1958. https://doi.org/10.1007/s11069-012-0294-2

KNMI. (2016, 30 september). KNMI – Orkaan Matthew actief in Caribisch gebied. knmi.nl. Consulted on 1 June 2022, from https://www.knmi.nl/over-het-knmi/nieuws/orkaan-matthew-actief-in-caribisch-gebied

Koch, R., USDA Foreign Agricultural Service, & International Agriculutral Internship Program. (2015, augustus). Assessment of Global Climate Change on the Caribbean Region (Nr. CB1514). USDA Foreign Agriculural Service. https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Assessment%20of%20Global%20Climate%20Change%20on%20the%20Caribbean%20Region_Miami%20ATO_Caribbean%20Basin_10-8-2015.pdf

Koks, E. E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M., Fraser, S. A., Hall, J. W., & Hallegatte, S. (2019). A global multi-hazard risk analysis of road and railway infrastructure assets. *Nature Communications, 10*(1). https://doi.org/10.1038/s41467-019-10442-3

Le Bars, D., Van der Linden, E., & KNMI. (2022, 11 mei). KNMI - Zeespiegel stijgt bij Caribisch Nederland net wat sneller. KNMI-klimaatbericht. Consulted on 1 June 2022, From https://www.knmi.nl/over-het-knmi/nieuws/zeespiegelstijging-bij-caribisch-nederland

Dullaart, J., van Manen, S. (2022). *The future coastlines of Bonaire: An assessment of the impacts of climate change on coastal inundation on Bonaire*. Vrije Universiteit Amsterdam

Manley, M., & Kim, Y. S. (2012). Modeling emergency evacuation of individuals with disabilities (exitus): An agent-based public decision support system. *Expert Systems with Applications, 39*(9), 8300–8311. https://doi.org/10.1016/j.eswa.2012.01.169

Markantonis, V., Meyer, V., & Schwarze, R. (2012). Review Article Valuating the intangible effects of natural hazards – review and analysis of the costing methods. *Natural Hazards and Earth System Sciences, 12*(5), 1633–1640. https://doi.org/10.5194/nhess-12-1633-2012

McMaster, R. B., Leitner, H., & Sheppard, E. (1997). GIS-based Environmental Equity and Risk Assessment: Methodological Problems and Prospects. *Cartography and Geographic Information Systems, 24*(3), 172–189. https://doi.org/10.1559/152304097782476933

McSweeney, C., New, M., Lizcano, G., & Lu, X. (2010). The UNDP Climate Change Country Profiles. *Bulletin of the American Meteorological Society, 91*(2), 157–166. https://doi.org/10.1175/2009bams2826.1

Menéndez, P., Losada, I. J., Torres-Ortega, S., Narayan, S., & Beck, M. W. (2020). *The Global Flood Protection Benefits of Mangroves*. Scientific Reports, 10(1). https://doi.org/10.1038/s41598-020-61136-6

Microsoft Bing Maps. (2022, 31 mei). Building Footprints. Microsoft - Bing Maps for Enterprise. Consulted on 1 June 2022, from https://www.microsoft.com/en-us/maps/building-footprints

Ministerie van Algemene Zaken. (2020, 17 januari). *Waaruit bestaat het Koninkrijk der Nederlanden?* Rijksoverheid.nl. Consulted on 25 Februari 2022, from https://www.rijksoverheid.nl/onderwerpen/caribische-deel-van-het-koninkrijk/vraag-en-antwoord/waaruit-bestaat-het-koninkrijk-der-nederlanden#:%7E:text=Bonaire%2C%20Sint%20Eustatius%2C%20Saba%20zijn,voor%20de%20kust%20van%20Venezuela

de Moel, H., & Aerts, J. C. J. H. (2010). Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. *Natural Hazards, 58*(1), 407–425. https://doi.org/10.1007/s11069-010-9675-6

Monna, J. (2016, 5 oktober). *Noodverordening voor Bonaire* | Caribisch Netwerk. Caribisch Netwerk | Caribisch Netwerk. Consulted on 1 June 2022, From https://caribischnetwerk.ntr.nl/2016/10/05/noodverordening-voor-bonaire/

Moore, W. R. (2010). The impact of climate change on Caribbean tourism demand. *Current Issues in Tourism, 13*(5), 495–505. https://doi.org/10.1080/13683500903576045

Newman, J. P., Maier, H. R., Riddell, G. A., Zecchin, A. C., Daniell, J. E., Schaefer, A. M., Van Delden, H., Khazai, B., O'Flaherty, M. J., & Newland, C. P. (2017). Review of literature on decision support systems for natural hazard risk reduction: Current status and future research directions. *Environmental Modelling & Software, 96*, 378–409. https://doi.org/10.1016/j.envsoft.2017.06.042

OSM:OpenStreetMap. (n.d.). OpenStreetMap. https://www.openstreetmap.org. Accessed on 1 June 2022, from https://www.openstreetmap.org/#map=15/12.1495/-68.2622

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N. K., Edenhofer, O., Elgizouli, I., Field, C. B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, L., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Jimenez Cisneroz, B., Kattsov, V., Lee, H., Mach, K.

J., Marotzke, J., Mastrandrea, M. D., Meyer, L., Minx, J., Mulugetta, Y., O'Brien, K., Oppenheimer, M., Pereira, J. J., Pichs-Madruga, R., Plattner, G. K., Pörtner, H. O., Power, S. B., Preston, B., Ravindranath, N. H., Reisinger, A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T. F., Tschakert, P., van Vuuren, D. and van Ypserle, J. P. (2014): *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change / R. Pachauri and L. Meyer (editors) , Geneva, Switzerland, IPCC, 151 p., ISBN: 978-92-9169-143-2.

QGIS.org. (n.d.). *Welcome to the QGIS project!* Consulted on 1 June 2022, from https://qgis.org/en/site/

Rasmussen, D. J., Bittermann, K., Buchanan, M. K., Kulp, S., Strauss, B. H., Kopp, R. E., & Oppenheimer, M. (2018). Extreme sea level implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature stabilization targets in the 21st and 22nd centuries. *Environmental Research Letters, 13*(3), 034040. https://doi.org/10.1088/1748-9326/aaac87

RLB: Rider Levett Bucknall. (2021, June). Caribbean report construction market intelligence. https://s31756.pcdn.co/americas/wp-content/uploads/sites/4/2021/06/2021-Caribbean-Report.pdf

Robinson, S. A. (2015). Climate change adaptation trends in small island developing states. *Mitigation and Adaptation Strategies for Global Change, 22*(4), 669–691. https://doi.org/10.1007/s11027-015-9693-5

Robinson, S. (2020). Climate change adaptation in SIDS : A systematic review of the literature pre and post the IPCC Fifth Assessment Report. *WIREs Climate Change, 11*(4). https://doi.org/10.1002/wcc.653

Sandin, S. A., Sampayo, E. M., & Vermeij, M. J. A. (2008). Coral reef fish and benthic community structure of Bonaire and Curaçao, Netherlands Antilles. *Caribbean Journal of Science, 44*(2), 137–144. https://doi.org/10.18475/cjos.v44i2.a2

Scandurra, G., Romano, A., Ronghi, M., & Carfora, A. (2018). On the vulnerability of Small Island Developing States: A dynamic analysis. *Ecological Indicators, 84*, 382–392. https://doi.org/10.1016/j.ecolind.2017.09.016

Schnitter, R., Verret, M., Berry, P., Chung Tiam Fook, T., Hales, S., Lal, A., & Edwards, S. (2018). An Assessment of Climate Change and Health Vulnerability and Adaptation in Dominica. I*nternational Journal of Environmental Research and Public Health, 16*(1), 70. https://doi.org/10.3390/ijerph16010070

Seetanah, B., & Fauzel, S. (2019). Investigating the impact of climate change on the tourism sector: evidence from a sample of island economies. *Tourism Review, 74*(2), 194–203. https://doi.org/10.1108/tr-12-2017-0204

Tiggeloven, T, Buijs, S., van Oosterhout, L. (2022). *Protecting Bonaire against coastal flooding: A participatory multi-criteria analysis of coastal adaptation options*. Vrije Universiteit Amsterdam

U.N.; Department of Economic and Social Affairs Sustainable Development. (n.d.). Small Island Developing States. sdgs.un.org. Consulted on 1 June 2022, From https://sdgs.un.org/topics/small-island-developing-states

UNCTAD (2017) Climate change impacts on coastal transport infrastructure in the Caribbean: enhancing the adaptive capacity of Small Island Developing States (SIDS), Climate Risk and Vulnerability Assessment Framework for Caribbean Coastal Transport Infrastructure. UNDA project 1415O.

UNDRR. (n.d.). Hazard. accessed at 1 June 2022, from https://www.undrr.org/terminology

UNISDR (United Nations International Strategy for Disaster Reduction). 2015. Sendai framework for disaster risk reduction 2015–2030. Geneva: UNISDR

UYARRA, M. C., CÔTÉ, I. M., GILL, J. A., TINCH, R. R., VINER, D., & WATKINSON, A. R. (2005). Island-specific preferences of tourists for environmental features: implications of climate change for tourism-dependent states. Environmental Conservation, 32(1), 11–19. https://doi.org/10.1017/s0376892904001808

van Beukering, P., Baertz, A., van Oosterhout, L., Schep, S. (2022a). *Non-Economic Loss and Damage from Climate Change on Bonaire: An Assessment of the Impacts of Climate Change on Cultural Heritage.* Vrije Universiteit Amsterdam

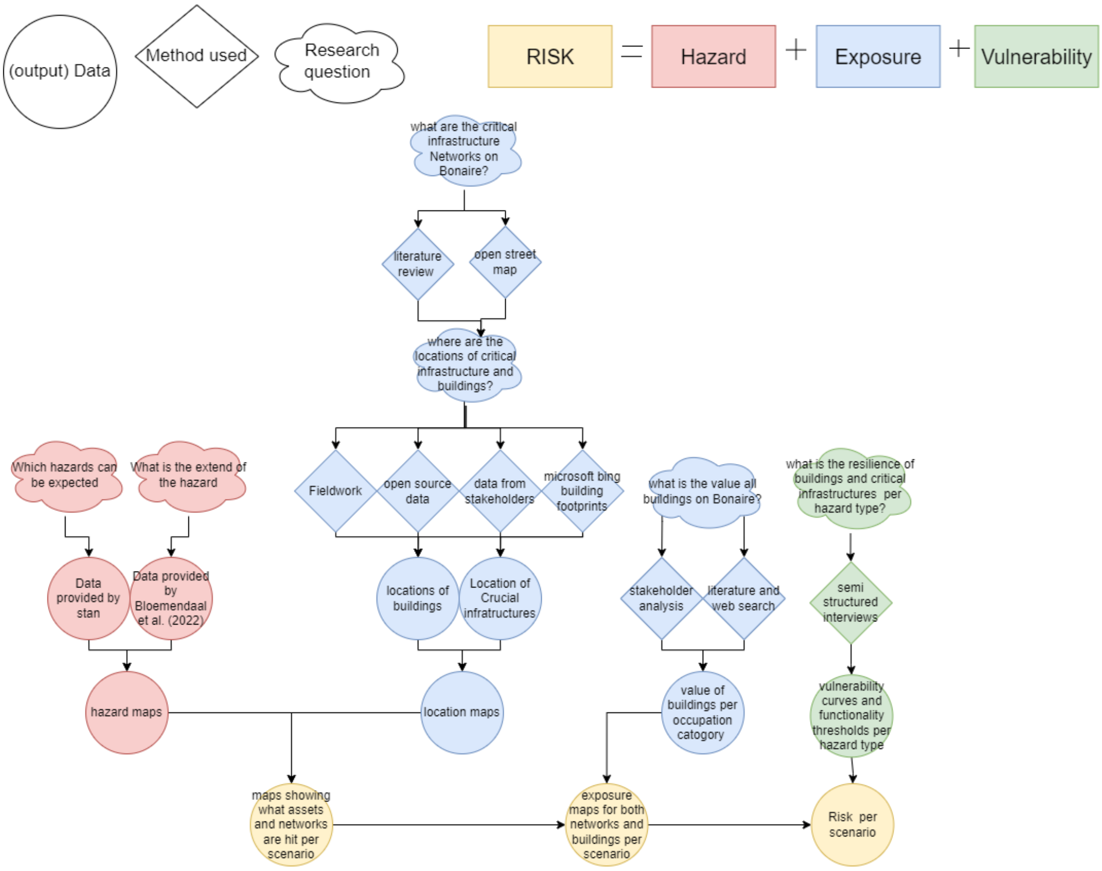
Verweij, P., Cormont, A., Nel, J., De Rooij, B., Jones-Walters, L., Slijkerman, D., Soma, K., Van Eurpen, M., Pourier, S., Coolen, Q., Mone, G., Bervoets, T., Clarenda, J., Van Slobbe, F., Christiaan, D., De Meyer, K., De Vries, Y., Eleana, R., Hoetjes, P., . . . Dominguez Teles, I. (2020). *A nature inclusive vision for Bonaire in 2050*. https://doi.org/10.18174/526467

Vousdoukas, M. I., Bouziotas, D., Giardino, A., Bouwer, L. M., Mentaschi, L., Voukouvalas, E., & Feyen, L. (2018). Understanding epistemic uncertainty in large-scale coastal flood risk assessment for present and future climates. *Natural Hazards and Earth System Sciences, 18*(8), 2127–2142. https://doi.org/10.5194/nhess-18-2127-2018

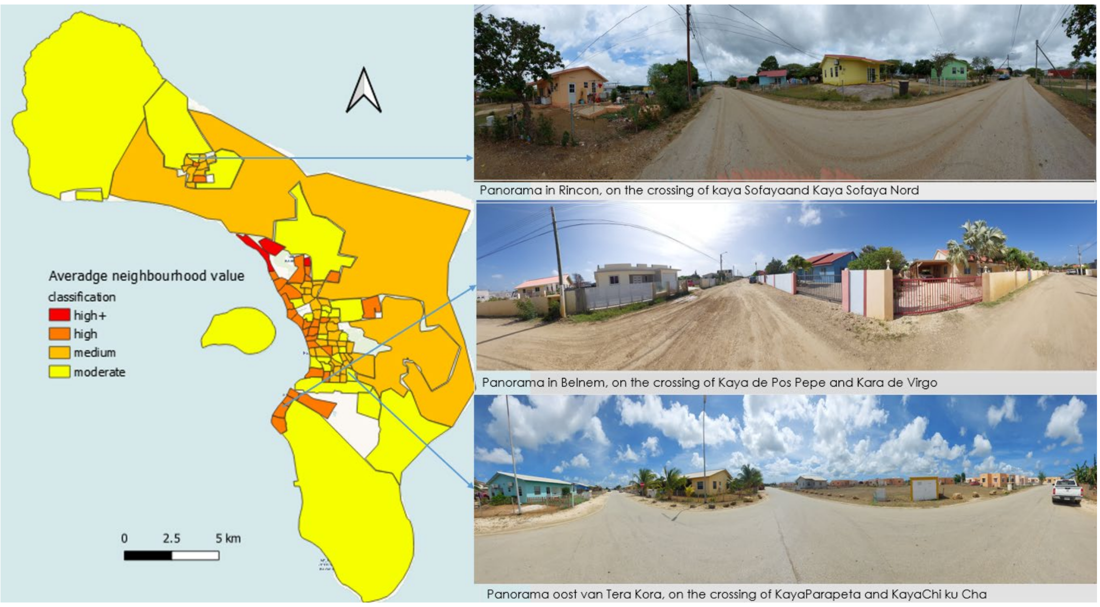
Ward, P. J., Blauhut, V., Bloemendaal, N., Daniell, J. E., de Ruiter, M. C., Duncan, M. J., Emberson, R., Jenkins, S. F., Kirschbaum, D., Kunz, M., Mohr, S., Muis, S., Riddell, G. A., Schäfer, A., Stanley, T., Veldkamp, T. I. E., & Winsemius, H. C. (2020). Review article: Natural hazard risk assessments at the global scale. *Natural Hazards and Earth System Sciences, 20*(4), 1069–1096. https://doi.org/10.5194/nhess-20-1069-2020

Wobus, C., Zheng, P., Stein, J., Lay, C., Mahoney, H., Lorie, M., Mills, D., Spies, R., Szafranski, B., & Martinich, J. (2019). *Projecting Changes in Expected Annual Damages From Riverine Flooding in the United States*. Earth's Future. https://doi.org/10.1029/2018ef001119

Annex A Schematic overview of the methodology



Annex B Map with geotag panoramas



Panorama in Rincon, on the crossing of kaya Sofayaand Kaya Sofaya Nord

Panorama in Belnem, on the crossing of Kaya de Pos Pepe and Kara de Virgo

Panorama oost van Tera Kora, on the crossing of KayaParapeta and KayaChi ku Cha

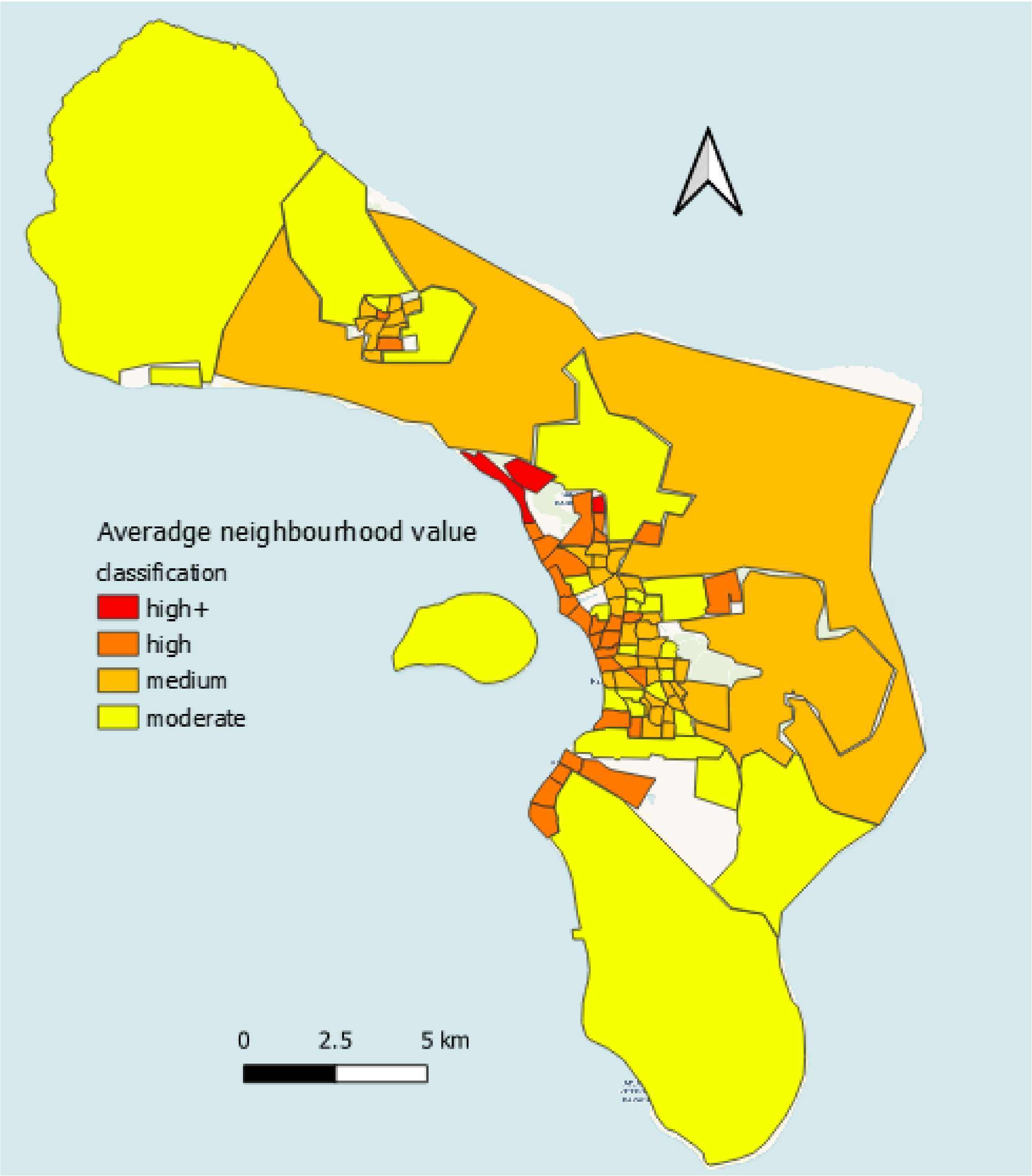
Annex C Table of classification of buildings

System	Subsytem	Includes
Energy	Power plant	Powerplant
	Oil storage	Bopec, Curoil
	Windmill	Windmill
Transportation	Roads	All road types
	Airport	Airport buildings
	Harbour	Harbour facilities
Drinkwater	Desalinisation plant	Desalinisation plant
	Drinkwater storage	Water storage
Waste	Saibon	Landfill
Health and first responders	Healthcare	Clinic, Docter, Dentist, Pharmacy
		Hospital
	Fire fighters	Fire Station
	Police	Police station, prison
	Genral Services	Town Hall(small), government offices
Education	Education	School, Kindergarten, Library
Commercial	Shops and retail	Retail trade, dept store
		Wholesale trade, warehouse medium
	Offices	Personal and repair services, garage/repair
		Prof/tech.buisiness services, office medium
		Banks
	Hospitality	Entertainment & recreation and restaurant
		Theatre, movie theatre, musea
		Hotels
	Industry	Industry
	Religious buildings	Church, other religious building
Residential	Residential	Modest
		Medium
		High
		High+
		Shed

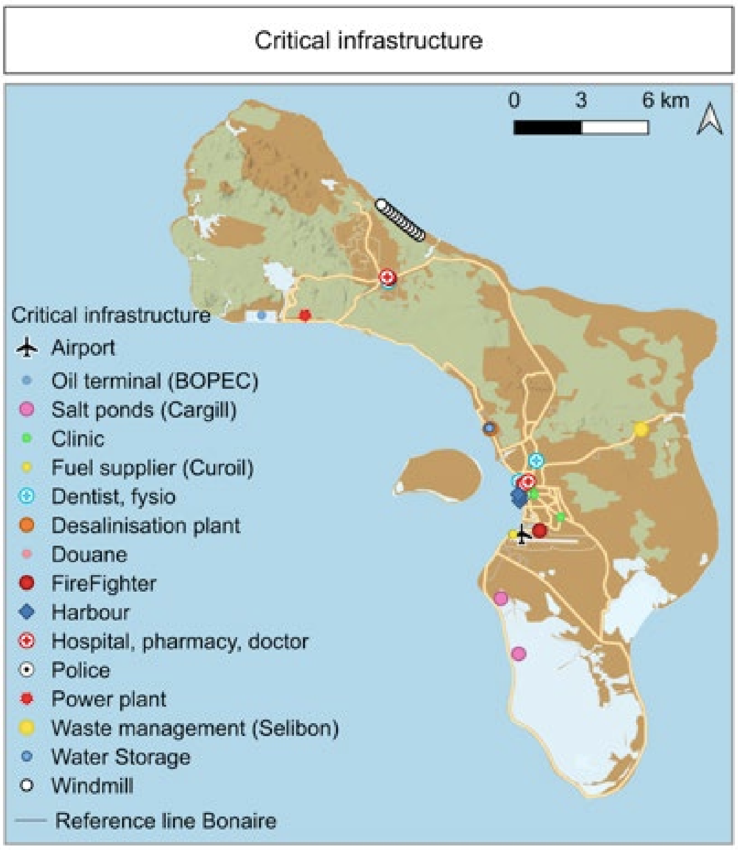
Annex D Value per square metre assumed in 2050 and from what source

System	Subsytem	Includes	Source	Year	Value in 2050 (per m2)
Health and first responders	Healthcare	Clinic, Docter, Dentist, Pharmacy	BCQS	2020	$ 5,074.36
		Hospital	FEMA, Hazus	2016	$ 6,688.31
	Fire fighters	Fire Station	FEMA, Hazus	2016	$ 4,658.64
	Police	Police station, prison	FEMA, Hazus	2016	$ 4,658.64
	Genral Services	Town Hall(small), government offices	FEMA, Hazus	2016	$ 2,739.84
Education	Education	School, Kindergarten, Library	FEMA, Hazus	2016	$ 3,464.65
Commercial	Shops and retail	Retail trade, dept store	RLB	2021	$ 2,700.73
		Wholesale trade, warehouse medium	RLB	2021	$ 2,859.60
	Offices	Personal and repair services, garage/repair	RLB	2021	$ 1,826.97
		Prof/tech.buisiness services, office medium	RLB	2021	$ 2,065.27
		Banks	RLB	2021	$ 4,686.57
	Hospitality	Entertainment & recreation and restaurant	BCQS	2020	$ 5,074.36
		Theatre, movie theatre, musea	FEMA, Hazus	2016	$ 3,347.14
		Hotel 5 star	RLB	2021	$ 5,163.17
		Hotel 3 star	RLB	2021	$ 3,018.47
	Industry	Industry	RLB	2021	$ 1,826.97
	Religious buildings	Church, other religious building	FEMA, Hazus	2016	$ 3,573.64
Residential	Residential	Modest	BCQS	2020	$ 1,772.00
		Medium	BCQS	2020	$ 2,335.82
		High	BCQS	2020	$ 3,624.54
		High+	BCQS	2020	$ 4,027.27
		Shed	RLB half of industry	2021	$ 913.48

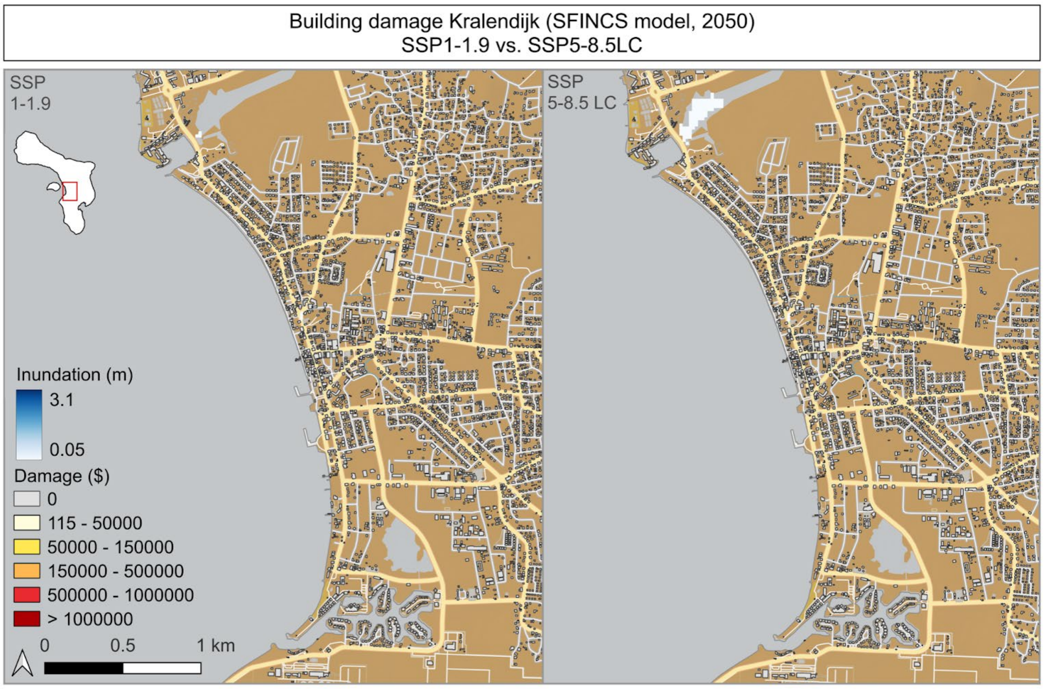
Annex E Overview of value per neighbourhood



Annex F Map showing location of critical infrastructure assets

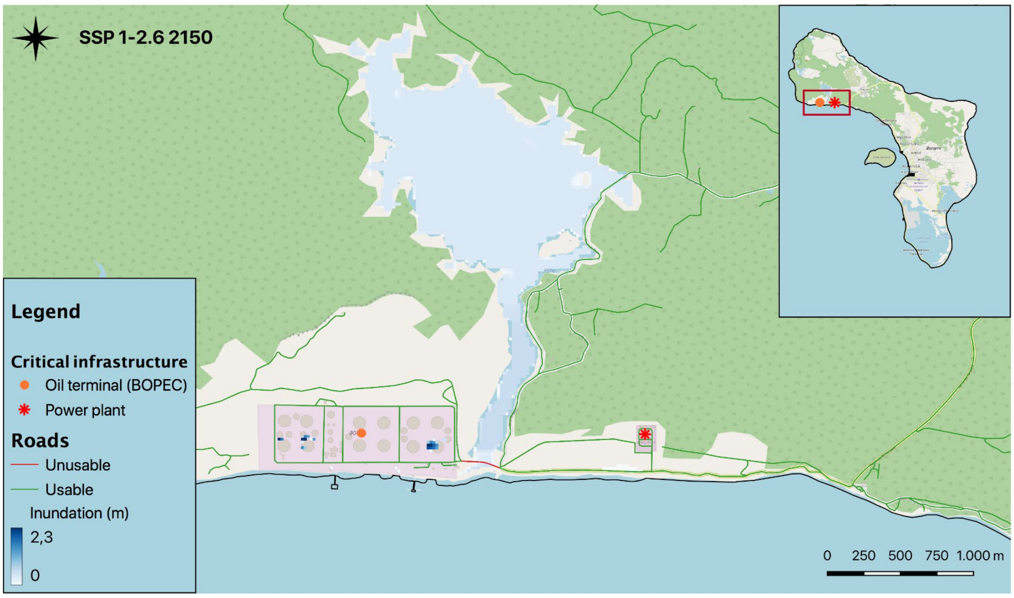


Annex G Inundation in Kralendijk in 2050 SSP 1-1.9 and SSP 5-8.5 LC

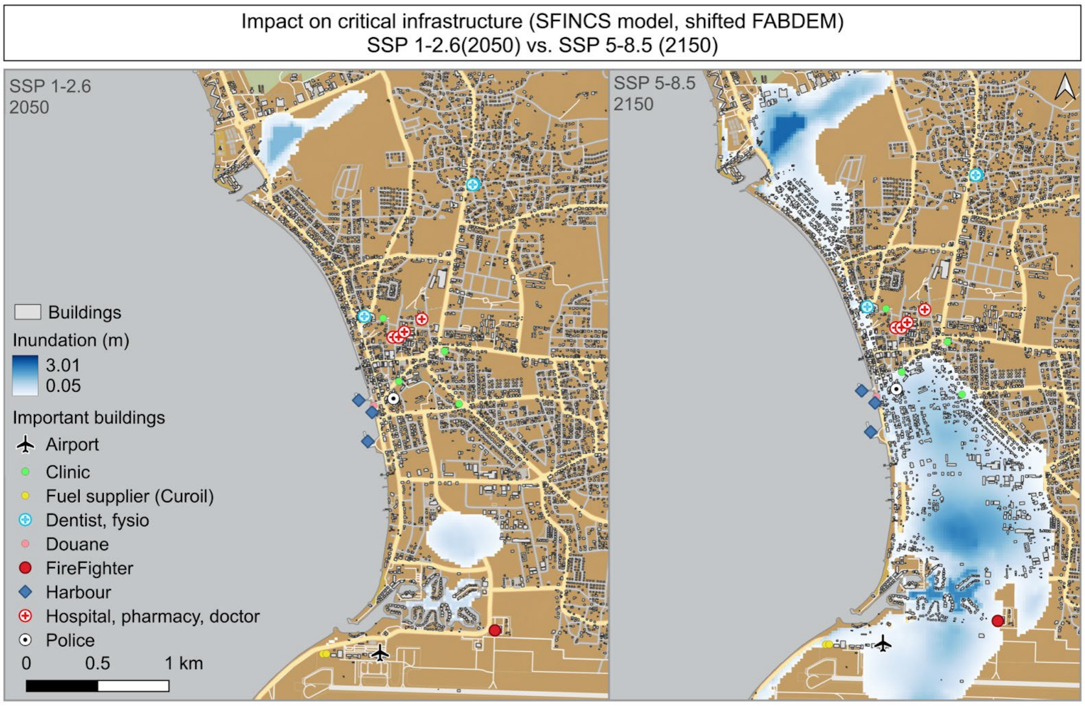


Building damage Kralendijk (SFINCS model, 2050)
SSP1-1.9 vs. SSP5-8.5LC

Annex H Inundation infrastructure to oil terminal (BOPEC) in 2150



Annex I Inundation in Kralendijk in 2050 SSP 1-2.6 and 2150 SSP 5-8.5 shifted DEM



Annex J Potential number of houses permanently inundated

Scenario	Year	Number of buildings hit (#)
SSP 1-1.9	2050	3
	2150	48
SSP 2-4.5	2050	3
	2150	103
SSP 5-8.5	2050	3
	2150	185