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The Impacts of Climate Change on Bonaire

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Report R-22/06
28 September 2022

This report is released by: Pieter van Beukering
Director Institute for Environmental Studies,
Vrije Universiteit Amsterdam

This report was commissioned by: Greenpeace Nederland
It was internally reviewed by: Charlotte Rappel

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Acknowledgements

We are grateful for the support we received during the research. First, we thank Greenpeace Netherlands for initiating this research project and providing us with the opportunity to study the impacts of climate change on Bonaire. Additionally, a grateful for the Bonairians for sharing their views with us, which helped us to better comprehend the local context and the issues they face. We would like to extend a special thanks to those who participated in our interviews; the valuable information they provided was indispensable to the research and generation of the results. Furthermore, we would like to thank the reviewers of our (sub)studies, namely WWF Netherlands, STINAPA, the Ministry of Agriculture, Nature, and Food Quality, Fuhikubo, Tourism Corporation Bonaire, Mangrove Maniacs, Bonaire Brandstof Terminals, and CBS Caribbean Netherlands. Their feedback provided direction and enabled us to validate the outcomes and generate robust results.

Contents

List of abbreviations

ABC (islands)	Aruba, Bonaire, Curaçao
AC	Air Conditioning
AHN	Algemeen Hoogtebestand Nederland
AT	Air Temperature
BAG	Basisregistratie Adressen en Gebouwen
CC	Climate Change
CE	Cultural Expert
CO2	Carbon Dioxide
DEM	Digital Elevation Model
GDP	Gross Domestic Product
GEM	Green Economic Model
GIS	Geographic Information System
HE	Health Expert
HG	High Growth
ICH	Intangible Cultural Heritage
IO	Input-Output
IPCC	Intergovernmental Panel on Climate Change
KNMI	Royal Netherlands Meteorological Institute
LC	Low Confidence
LG	Low Growth
MCA	Multi Criteria Analysis
NGO	Non-governmental Organisations
OLB	Public Entity Bonaire
PAHO	Pan American Health Organization
PM	Participatory Mapping
PPP	Purchasing Power Parity
RCP	Representative Concentration Pathway
RHI	Reef Health Index
RIVM	National Institute for Public Health and the Environment
RLB	Rider Levett Bucknall
RP	Return Period
SFINCS	Super-Fast Inundation of Coasts
SIDS	Small Island Development States
SLR	Sea Level Rise
SSP	Shared Socioeconomic Pathway
SST	Sea Surface Temperature
TC	Tropical Cyclones
TCB	Tourism Corporation Bonaire
TCH	Tangible Cultural Heritage
TWL	Total Water Level
UN	United Nations
USD	United States Dollar
WHO	World Health Organization

Executive summary

Small islands are particularly vulnerable to climate change because of their fragile ecosystems, small economies, and often extensive, low-lying coastal areas. Therefore, small islands, such as present in the Caribbean Netherlands, are expected to suffer excessively from rising temperatures, changes in precipitation, sea-level rise, coral bleaching, cyclones, droughts and floods. Despite this widespread conviction, scientific evidence of these effects in the Caribbean Netherlands is scarce, and as a result, limited adaptation strategies are developed or implemented by local and Dutch governments.

In this study, an analysis is conducted assessing the **impacts of climate change** for the island of Bonaire. Given the uncertainty regarding the actual level of climate change in the future, four universally recognised scenarios are simulated, ranging from an optimistic scenario "SSP1-1.9" (corresponding to a mean temperature rise of 1.4°C at the end of the 21st century relative to pre-industrial levels), which assumes climate change will modestly increase relative to current levels, to a pessimistic scenario "SSP5-8.5" (corresponding to a mean temperature rise of 4.4°C at the end of the 21st century relative to pre-industrial levels), which suggests very high levels of climate change. Impacts are measured and reported at different moments in time, mainly looking at the years 2050 and 2150, representing short-term and long-term effects of climate change, respectively. A mix of methods from various scientific disciplines are used to estimate the impacts of climate change, including climate and flood models, ecological-economic models, as well as social-science methods such as social media analysis, participatory mapping and key-informant interviews. Although the sub-components of the study are systematically aligned and integrated, four topics can be distinguished: the estimation of the biophysical impacts, the modelling of economic effects, the identification of socio-cultural effects, and the exploration for potential adaptation options.

First, we analyse the expected **bio-physical and environmental changes** associated with different climate projections. The applied flood model simulations reveal that, already by 2050, sea-level rise will cause permanent inundation of parts of the low-lying nature reserves of the saliñas, Lac Bay and Klein Bonaire, thereby altering the extent and dynamics of these areas. Increasing storms are expected to double this inundated area, with an estimated surface of around 8 km^2 comprising both permanently and temporarily flooded areas. With climate change increasing over time, sea-level rise and coastal storm inundation will further expand the flooded surface area of Bonaire by 2150, ranging from 14.3 km^2 to 32.2 km^2, depending on the climate scenario. These flood simulations clearly identify Bonaire's high-risk built-up areas: Belnem and other areas in Kralendijk. But this is not the complete picture; coral reefs are extremely vulnerable to temperature increase, acidification and extreme storms, and our study predicts significant declines of the reef health index of the coral reefs of Bonaire in three of the four climate scenarios already by 2050. Since coral reefs currently act as a natural buffer against waves on Bonaire, the loss of this important ecosystem will further amplify the flooding caused by climate change.

Second, we estimate the expected **economic effects** associated with climate change, including impacts on economic development, the built environment and infrastructure. The economic impact is mainly felt through damage costs caused by floods as well as negative effects on tourism caused by the loss of corals. Storms are expected to largely

affect Kralendijk and Belnem under the worst climate scenario, resulting in estimated damage costs of US$317 million by 2050. Since permanently inundated buildings are not included in the damage costs projections, these costs are likely to be on the conservative side. As a large part of the damaged structures are in key areas, and numerous coastal and southern roads on the island will be unusable, flood hazards will not only disrupt entire neighbourhoods but also make it impossible for emergency services to reach these areas and buildings. Moreover, we estimate that the economy will be negatively affected by the loss of coral reefs since numerous valuable dive sites will be severely degraded. In the worst climate scenario, coral reef degradation may lead to a reduction of quality dive sites from 86 to 12 and a subsequent reduction in dive tourist arrivals of more than 100 thousand visitors by 2050, causing a contraction in Bonaire's economy of roughly 25%.

Third, we identified the expected **socio-cultural effects** associated with the climate change in terms of loss of cultural heritage and health impacts. The tangible cultural impact is felt through the permanent flooding of key locations with cultural significance for Bonaireans, such as the slave huts and the house at Boca Slagbaai. Loss of cultural heritage may have severe impacts on society, as it may lead to a decline in cultural identity and social cohesion. The intangible cultural impact of extreme weather events and rising temperatures includes pressures on the traditional ways of life of Bonaire, including fishing, agriculture, and festivities. Additionally, numerous experts on Bonaire reported that the effects of climate change on Bonaireans' health, such as changes in vector-borne disease incidence and heat-related stress, are already observed and are likely to increase with climate change. This impact is further magnified with the ageing of the population on Bonaire, making the people even more susceptible to heat-related stress disorders.

Fourth, we evaluate several **adaptation measures** to understand which management alternatives Bonaire could implement to cope with the negative consequences of climate change. Potential adaptation strategies include nature-based solutions such as the conservation of coral reefs and the restoration of coastal vegetation, which contribute to the prevention of flooding. Moreover, decision-makers should consider investing in various heat mitigation strategies, such as climate-sensitive building designs, artificial and natural shading, as well as information programmes to educate the population on how to protect themselves from high-temperature exposure. We conclude that, although the impacts of climate change necessitate immediate action, decision-makers should also focus on the longer term, such as 2150 and beyond, as the effects of climate change will worsen significantly over time.

Since our study did not address all effects of climate change and since climate research with regional and local precision is still in development, the impacts presented in our study can be regarded as preliminary lower-bound estimates. In other words, additional research may generate estimates of even more severe impacts of climate change in Bonaire. In addition, we like to emphasise that there is little knowledge about the effects of climate change in the Dutch Caribbean at the present time. This study is the first attempt to map and quantify a broad range of climate change effects for Bonaire, which is only one of the six islands in the Caribbean Netherlands. Because the research results are unique for Bonaire, we recommend conducting similar studies for the other Caribbean islands in the Kingdom of the Netherlands.

1 Introduction

Climate change (CC) is the defining concern of our time (UN, n.d.). Small islands are disproportionately affected by climate change, which is unfair especially considering their minor contribution to global greenhouse gas emissions (IPCC, 2021; PAHO, 2019). Small islands are particularly vulnerable because of their small economies and often low-lying, large coastal areas which foster their lifestyles and cultures (Carabine & Dupar, 2014; Macpherson & Akpinar-Elci, 2013). The Intergovernmental Panel on Climate Change (IPCC) (2022) is confident that small islands will suffer excessively from temperature increases, changes in precipitation patterns, sea level rise, coral bleaching, tropical cyclones, droughts, and storms, as a result of climate change.

Caribbean small islands are not exempt from these negative effects of climate change (Nurse *et al*., 2014). For future climate conditions in the Caribbean region, the IPCC predicts higher temperatures, sea level rise and changing precipitation patterns (Akpinar-Elci & Sealy, 2014; Nurse *et al*., 2014). These projected changes will produce environmental, economic, and social damage and put further pressure on small islands (Akpinar-Elci & Sealy, 2014; Dutch Caribbean Nature Alliance, 2019). In fact, small islands in the Caribbean are already being affected: by sea level rise and weather changes, and indirect climate change effects, such as impacted fisheries and reduced food security (Alliance of Small Island States, 2009).

Despite the widespread conviction that anthropogenic warming will have serious effects on the island's environment and inhabitants (Akpinar-Elci & Sealy, 2014; Dutch Caribbean Nature Alliance, 2019), it is unclear what environmental changes will occur under various climate scenarios and how they will translate into direct physical risks to people and communities, and indirect consequences for their lifestyles.

Therefore, this report provides an overview of environmental changes and associated consequences for the citizens of Bonaire by addressing three components. First, we analyse the expected environmental changes associated with different climate projections, such as levels of coastal inundation, coral degradation and temperature changes. Second, we estimate the expected socio-economic effects associated with the climatic changes. This includes impacts on economic development, the built environment. Third, we identified the expected social effects associated with the climatic change in terms of loss of cultural heritage and health impacts. Fourth, we evaluate several climate adaptation measures to understand which management alternatives the Bonairean communities could implement to cope with the negative consequences of climate change.

The remainder of this report is structured as follows. Chapter 2 addresses the context of the study by describing environmental, social and economic characteristics as well as various essential tropical coastal ecosystems on Bonaire. Chapter 3 presents the overall research framework and the range of methodological approaches applied in this holistic report. Chapter 4 to 11 present the main findings of the study, including biophysical impacts, economic and societal impacts, and, finally, adaptation measures. The implications for Bonaire and the wider Caribbean region, as well as the limitations of this study are explained in chapter 12. Chapter 13 concludes the study and provides recommendations.

2 Study site Bonaire

This chapter provides background information about the current situation of Bonaire and its inhabitants, thereby contextualising the environmental and climatic conditions, as well as the socio-economic and political characteristics.

2.1 Macro environmental analysis

2.1.1 Environmental characteristics

Bonaire is a small island (288 km2) located in the Caribbean Sea, 80 km north off the coast of Venezue and has been a public entity within the Netherlands since the Netherlands Antilles dissolved in 2010. Bonaire's terrain is predominantly low-lying and covered by low thorny vegetation (Uyarra *et al*., 2005). The island exhibits a semi-arid steppe, but also tropical climate with alternating wet and dry seasons ranging from October to January and February to May, respectively. As Bonaire is located in the Southern Caribbean Dry Zone, its climate is drier compared to the rest of the Caribbean (Meteorological Department Curaçao, n.d.; Verweij *et al*., 2020). The tropical climate exhibits small temperature differences between seasons with seasonal mean temperatures between 26°C and 29°C (Meteorological Department Curaçao, n.d.; Schmutz *et al*., 2017).

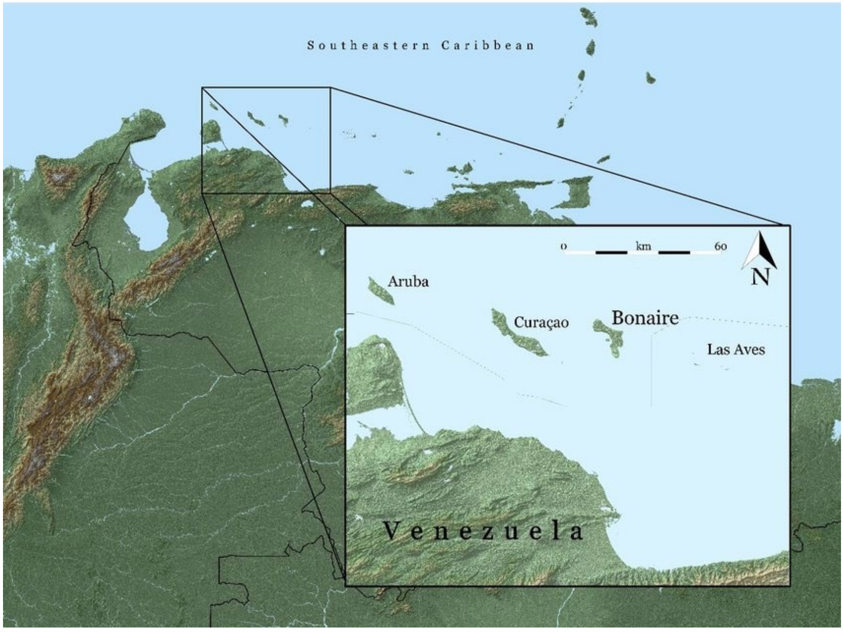


Figure 2-1 The ABC islands (Antczak, 2018, p.14)

The waters surrounding Bonaire and its satellite island, Klein Bonaire, are an exemplary model of self-financing marine protected areas, as they have been well managed and are fully protected to 60m depth since 1979 (Spalding *et al*., 2001). However, as with other areas in the Caribbean, the reefs around the island have suffered from increased pressures of climate change, such as bleaching events and diseases (Spalding *et al*., 2001), and local pressures, such as erosion and nutrient loading.

2.1.2 Social circumstances

Between 2010 and 2022, the population of Bonaire has grown from 15,500 to 22,600 people (CBS, 2022). This growth was mainly attributable to migration and is expected to continue (CBS, 2022). As shown in Figure 2-2, the population is diverse, with residents from the Caribbean Netherlands, Southern, Central, and North America, and the European Netherlands. In 2020, the Bonairian population of working age (15 to 74 years) was approximately 16,500, of which 70% were employed and only 4.6% of unemployed individuals were actively seeking employment.

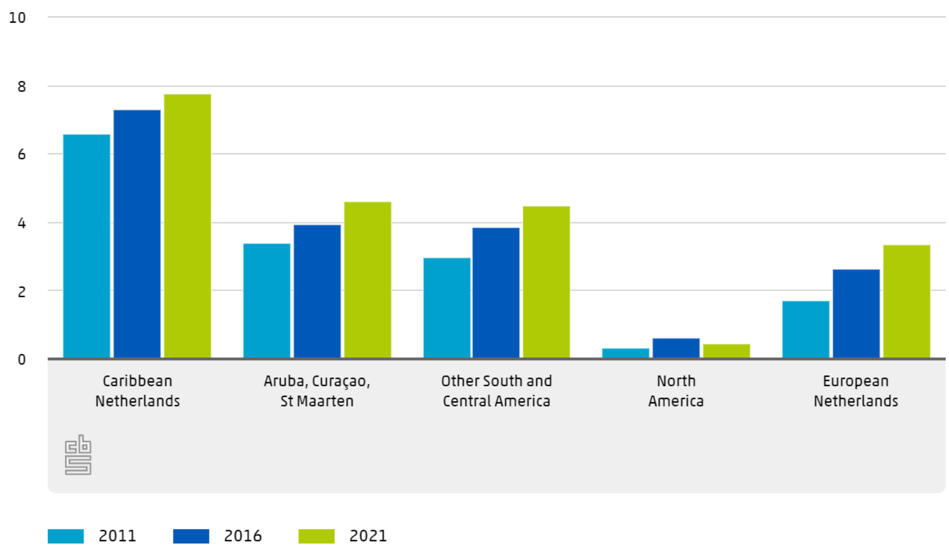


Figure 2-2 Bonaire population by region of birth - x 1,000 (Statistics Netherlands, 2021)

Compared to the rest of the Netherlands, income levels are low, with an average of 31,900 USD per household in 2020 compared to 41,600 USD in the rest of the Netherlands. Considering the low(er) income levels and the high costs of living in Bonaire, many Bonairians have difficulties making ends meet (Netherlands Institutes for Human Rights, 2016; Nationale Ombudsman, 2022). In purchasing power parity (ppp) terms, it is estimated that the purchasing power of Bonairians is 65% lower than European Netherlands residents in 2017 (Sociaal en Cultureel Planbureau, 2015). For instance, food on the island is already 44% more expensive than in the European Netherlands (Verweij *et al.*, 2020). Although the Bonairian inhabitants saw gains of purchasing power in 2019 (CBS, 2021), this is expected to significantly decrease considering the steep inflation experienced since 2021 (CBS, 2022). In addition, Bonaire's income inequality is significantly higher than in the European Netherlands. Expressed in terms of the Gini coefficient - which equals 0 in the case of total equality and 1 in the case of total inequality -, Bonaire's gini index amounted to 0.39 in 2020 relative to 0.29 in the European Netherlands. Finally, when comparing economic performance, Bonaire's GDP per capita in 2019 amounted to only 49% of the European Netherlands. The island mainly relies on imports for goods and resources as these are hardly produced locally.

The experienced poverty can have significant consequences on health; 27% of people in the Caribbean Netherlands suffer from serious weight problems due to unhealthy eating habits and lifestyles (Netherlands Institutes for Human Rights, 2016). The Institute for Human Rights furthermore stated that on Bonaire, there is a clear division between luxury residences, often populated by European Dutch people, and run-down homes in the outlying neighbourhoods. For vulnerable groups, such as people with a disability and the elderly, there are insufficient housing facilities.

2.1.3 Economic development

Bonaire's GDP increased to USDm 553 in 2019, averaging a yearly volume growth of 2.7% since 2012 (CBS, 2020). In terms of economic size, Bonaire's GDP is similar to other Small Island Developing States (SIDS) such as Tonga (USDm 512) and Dominica (USDm 470) (World Bank, 2021).

The economic importance of tourism to Caribbean SIDS is significant. Tourism is seen as a viable and, at times, the only pathway to the economic development of small and isolated economies (Pratt, 2015). Similarly, Bonaire's economy is firmly based on tourism, particularly the mainstay activity of scuba diving (KVK Bonaire, 2020; De Meyer, 1998). The island is home to a unique marine environment that sustains high biodiversity and an abundance of coral reefs and tropical fish (Bak *et al*., 2005). These natural assets have been the driving force behind exponential tourism growth over the last decades (Uyarra *et al*., 2005).

The "Centraal Bureau voor de Statistiek" (CBS) estimated in 2012 that the Direct GDP from tourism amounted to 16.3% of total GDP. Table 2-1 reveals the relatively high exposure of Bonaire to tourism expenditures compared to other tourism countries. The tourism sector is a far-reaching system that serves as the backbone of Bonaire's economy, maintaining and even encouraging growth in other vital industries (Schep *et al*., 2013). Therefore, the expectation is that the indirect GDP contribution to tourism is much higher than 16.3%. Tourism provides private income and public tax revenues that support education, public services, employment, and infrastructure. However, the strong reliance on tourism assets subjects the local population to external rather than indigenous resources. Since Bonaire is relatively limited in size and natural resources, the lack of a diversified local economy makes it inherently sensitive to exogenous shocks (Spies *et al*., 2015; World Bank, 2021).

The number of tourists arriving on Bonaire has been steadily increasing since 2001, although the total tourist arrivals sharply declined between 2020 and 2021 due to COVID-19 restrictions. The annual number of stay-over tourists (i.e., tourists arriving by plane) reached its peak in 2019 when 158 thousand tourists visited the island. The Tourism Corporation Bonaire (TCB) aims for 200 thousand stay-over tourists by 2027 to make the tourism industry 'the economic engine' of the island (Croes *et al*., 2019). Similarly, the number of cruise tourists that disembarked on the island peaked in 2019 at 433 thousand (CBS, 2020). Compared to the relatively small population of Bonaire, the tourism industry is of substantial size. Together with population growth and migration, these socio-economic developments have been leading to urban sprawl along the coast.

Table 2-1 Tourism Direct GDP of selected tourism countries

Caribbean	Year	% of total GDP	Europe	Year	% of total GDP
Aruba	2013	20.0	Montenegro	2009	10.0
Bahamas	2004	21.6	Iceland	2017	9.0
Bermuda	2018	5.4	Greece	2017	7.0
Bonaire	2012	16.3			
Dominican Republic	1996	9.9			
Jamaica	2018	9.0			

2.1.4 Political status

After the Netherlands Antilles dissolved in 2010, Bonaire became a public entity, which is comparable to a municipality, within the Netherlands (Government of the Netherlands, 2022), meaning they are jointly ruled by the island administration and the Dutch government. Although not a self-governing entity within the Kingdom, local affairs are governed by an appointed Mayor (gezaghebber) and the Executive Counsel, members of which are appointed by the elected Island Counsel.

SIDS often lead the way in international climate negotiations (WHO, 2021a). However, upon signing the Paris Agreement, the Netherlands declared that the Paris Agreement would only apply for the European part of the Kingdom. As such, the Paris agreement does not apply to the islands in the Dutch Caribbean.

2.2 Ecosystem analysis

2.2.1 Coral reefs

The coastal waters surrounding Bonaire are home to coral reefs that harbour a high level of biodiversity and form a vital asset for the island and its inhabitants. Coral reefs surround the island, both on the leeward (western) side of the island as well as the windward (eastern) side of the island (Bakker *et al*., 2019). The health of the Bonairian reefs is estimated to be higher compared to the average for the Caribbean region (Jackson *et al*., 2014), signifying their importance for biodiversity conservation. The entire coastal zone up to a depth of 60 metres, covering an area of some 27 square kilometres, has been declared a national marine park (i.e. Bonaire National Marine Park) and thus all coral reefs in Bonaire enjoy a protected status (STINAPA, 2022).

Coral reef ecosystems provide numerous benefits to society on Bonaire, through a variety of ecosystem services. Ecosystem services are defined by Daily (1997) as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life". Ecosystem services provided by the Bonairian reefs are diverse, ranging from providing a nursery ground for commercial fish species, to providing natural coastal protection through decreasing wave intensity, to forming a vital asset for the tourism industry through divers that visit the island for its beautiful reefs. In this way the coral reefs provide a large contribution to wellbeing on Bonaire. Any detrimental changes to their existence could have a significant impact on the ecosystem services provided by the reefs, and thus might have a significant impact on wellbeing on the island.

Apart from a variety of local factors that negatively affect the reef, such as erosion and pollution, one of the most pressing threats to coral reefs around Bonaire is climate change. The IPCC (Bindoff *et al*., 2019) states with high confidence that coral reefs in warm water regions are expected to significantly decrease in the density and size of coral reefs, even in a scenario where global warming is limited to 1.5 degrees Celsius, with higher temperatures leading to faster degradation of coral reefs. The primary drivers for this are an increase in thermal stress, ocean acidification and increased storm damage (Hoegh-Guldberg *et al*., 2017). These in turn lead to coral bleaching events and mass mortality events, as well as reduced coral recruitment and growth (Hoegh-Guldberg *et al*., 2017). Mass coral bleaching events are predicted to occur on a near annual basis in the Caribbean region by 2100 under all scenarios that exceed a global temperature rise of 2 degrees Celsius by 2100 (Hoegh-Guldberg *et al*., 2017; Figure 2-3). As shown in Figure 2-3, annual mass mortality events are expected to occur throughout the Caribbean by 2100 under the most extreme RCP8.5 climate scenario modelled by the IPCC, which assumes a continuous rise in GHG emissions in the 21st century. By this point it is plausible that coral reefs will have completely disappeared, potentially well before 2100 given the frequency of mass mortality events earlier in the century (Figure 2-3). The effects of climate change on coral reefs are further amplified by local stressors (de Bakker *et al*., 2019). On Bonaire, these local stressors include erosion due to grazing by wild goats, mechanical damage from human activity on the reefs through diving and sailing, and coastal development (de Bakker *et al*., 2019).

It is obvious that the services provided by Bonaire's diverse (coastal) ecosystems contribute in a variety of ways to the lives and well-being of the island's inhabitants, and that a number of (local) factors may have a detrimental impact on the health of these ecosystems. Within the scope of this study, the effects of climate change on the quality of Bonaire's coral reefs and their effects on economic development are the focal point. Bonaire's other coastal ecosystems and associated services are integrated and reflected on in this study, but they are not subjected to an in-depth ecological analysis of the effects of climate change on their health and conditions.

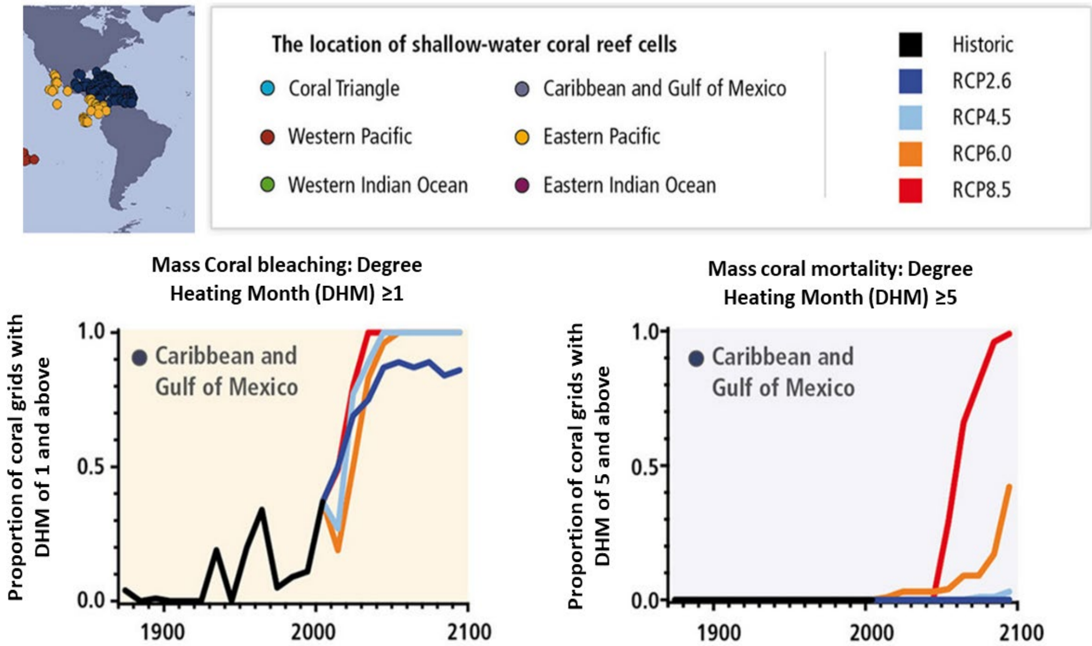


Figure 2-3 Project occurrence of mass coral bleaching events and mass coral mortality events up to 2100 under IPCC climate change scenarios. (Source: Hoegh-Guldbergt et al. 2017)

2.2.2 Beaches

Bonaire is only scarcely endowed with beaches, and of the current beaches the majority are comprised of washed-up coral rubble. White sand beaches are only found on select sites, including around the Sorobon and Lac Bay area, at Bachelor beach near Belnem, and on Klein Bonaire. This scarcity of beaches is mainly due to the steep dropoff of the coastline around Bonaire limiting sand availability within the shallow waters. Coupled with high wave energy along the coasts, beaches tend to only form in protected areas with wide, shallow beachfronts (DCNA, 2019).

Despite the limited number of beaches in Bonaire, this ecosystem provides an important breeding and foraging habitat for many species of coastal birds and sea turtles (Debrot *et al*., 2018). While the beaches are not the main reason for tourists to come to Bonaire, beaches do attractively complement the travel experience of many visitors. Moreover, these beaches provide important environmental services to locals, who visit these areas for the frequent family visits, thereby maintaining strong social bonds in a pleasant environment. For example, Donkey and Bachelor's beach are the beaches that are often used by the Bonairians, and traditions include camping on Donkey Beach for the Easter weekend. Finally, beaches also function as a natural buffer for coastal protection.

Similar to many other ecosystems in Bonaire, increasing pressures on beaches consist of climate change (e.g. sea level rise and higher temperatures), tourism, urban development, invasive species, pollution and illegal mining of sand (Debrot *et al*., 2018). The iconic Pink Beach in southern Bonaire has previously been destroyed by a storm that washed the pink sand away (CE1; Natural disasters Bonaire, n.d.). Another phenomenon threatening Bonaire's culturally significant beaches are Sargassum blooms. Sargassum is a floating macroalgae whose blooms in the Caribbean Sea appear to have become more frequent and intense (Wang & Hu, 2017). This increase in Sargassum blooms can be attributed to rising sea surface temperatures due to climate change and nutrient enrichment in the sea (Wang *et al*., 2019). Accordingly, a lot more Sargassum than usual has been washed onto Bonaire's coasts in the past years, where it can completely cover beaches.

2.2.3 Mangroves

Bonaire hosts mangrove forests mainly located on the south-eastern part of the island bordering the western and northern shores of Lac Bay. The forest at Lac Bay is a protected area and a certified Ramsar Wetland. Mangrove forests cover some 365 hectares on Bonaire (DCBD, 2019) and are primarily composed of red mangrove (Rhizophora mangle) and black mangrove (Avicennia germinans) trees (Davaasuren & Meesters, 2012). The entire Lac Bay lagoon has been declared a RAMSAR site, signifying its important natural characteristics (Debrot, Meesters & Slijkerman, 2010). The mangroves are expanding into the lagoon as a result of erosion, leading to sediment deposition in the lagoon offering new habitat for mangrove trees.

Mangroves form important ecosystems for numerous species and provide a suite of ecosystem services to society. In terms of biodiversity, mangroves form nursery habitat for a variety of fish and other animal species that take shelter between the roots of the trees (Robertson & Duke, 1987; Nagelkerken *et al*., 2008). Ecosystem services that these ecosystems provide include carbon sequestration, coastal protection through wave mitigation, fishing opportunities, water filtration through sediment uptake and various cultural services (Himes-Cornell, Pendleton & Atiyah, 2018). On Bonaire, the mangroves offer unique ecotourism opportunities through guided canoe tours.

The mangrove forests around Lac Bay are in relatively good health at present, but there are a number of threats and natural processes that can have significant effects on the extent and quality of the forests in the future (Debrot *et al*., 2018). On a local level, the landward mangrove forests are retreating due to sedimentation raising up the land while the seaward mangroves are expanding (Debrot *et al*., 2018). This is a natural process in mangrove ecosystems, but is amplified by erosion resulting from overgrazing by feral goats (Hylkema *et al*., 2014). On a global level, climate change is expected to have certain negative effects on mangrove forests. The primary effects of climate change that can be expected to have an effect on mangroves are: sea level rise, changing precipitation patterns, temperature rise and storm damage (Ward *et al*., 2016). The first three effects can lead to changes in habitat conditions that exceed tolerance levels, in terms of salinity and ambient temperature (Ward *et al*., 2016). Storm damage can occur when an increase in hurricane intensity leads to uprooting and defoliating of mangrove trees (Imbert, 2018). Lastly, it appears that decomposing Sargassum that washes upon the coastline in irregular events can have a negative effect on mangrove root systems (Hernández, Morell & Armstrong, 2022). These Sargassum influx events are increasing, with one proposed cause being climate change leading to warmer sea surface temperatures (Wang *et al*., 2019). When combined, these threats may impact mangrove health on Bonaire and threaten the biodiversity values and ecosystem services that these ecosystems provide.

2.2.4 Seagrasses

Seagrasses are the only angiosperms or flowering plants living submerged in seawater (Townsend, 2012). On Bonaire, Lac Bay is the biggest bay and consists of one the largest and most pristine seagrass habitats in the Caribbean Netherlands (Debrot *et al*., 2019; Govers *et al*., 2014a). This bay contains four species of seagrass. Turtle grass (Thalassia testudinum) is the dominant species but often coexists with manatee grass (Syringodium filiforme), shoal grass (Halodule wrightii), Halophila stipulacea (a non-indigenous Caribbean seagrass species), and widgeon grass (Ruppia maritima, a grasslike annual or perennial herb but not a seagrass species) (Debrot *et al*., 2019; Govers *et al*., 2014a,b; Smulders *et al*., 2017). In addition to Lac Bay, seagrass also occurs in other bays on Bonaire, e.g., in several saliñas, as well as around Klein Bonaire.

The seagrass ecosystems on Bonaire are biologically productive and ensure multiple ecosystem services such as coastal protection to attenuate waves or reduce tidal currents (Christianen *et al*., 2013; James *et al*., 2020), the stabilization of sediments to prevent erosion (Bos *et al*., 2007; Maxwell *et al*., 2016) as well as carbon sequestration to mitigate climate change (Duarte *et al*., 2005, 2010; Fourqurean *et al*., 2012; Johnson *et al*., 2020; Kennedy *et al*., 2010). Moreover, they support biodiversity by providing food and habitat to many organisms (Heck *et al*., 2003; Nagelkerken *et al*., 2000; Valdez *et al*., 2020). Since the seagrass ecosystems offer valuable ecosystem services on Bonaire, seagrasses are considered as important foundation species.

Climate change will influence seagrass' physiology, distribution and function as a result of increasing seawater temperature, CO_2 uptake, sea level rise, and a change in hydrology, salinity and nutrient concentrations (Brouns, 1994; Short & Neckles, 1999). However, it is not known to what extent climate change will affect seagrass ecosystems as the changes that will occur in seagrasses are hard to predict (Short & Neckles, 1999). Currently, the seagrasses on Bonaire are experiencing stress that have been caused by anthropogenic activities including eutrophication and pollution via land-based sediment and nutrient run-off (Debrot *et al*., 2013; Govers *et al*., 2014b; Slijkerman *et al*., 2011). Eutrophication refers to the condition of nutrient and mineral enrichment in the aquatic environment (Townsend, 2012). Over time, an increased nutrient load is associated with a relatively higher epiphyte, macroalgae and phytoplankton biomass causing light attenuation. Furthermore, the influx of pelagic Sargassum rafts has also recently become a threat to Bonaire's seagrass beds and mangrove forests as Sargassum accumulates on these coastal ecosystems (López-Contreras *et al*., 2021; Van Tussenbroek *et al*., 2017; Tjong, 2020). These masses of Sargassum decompose and release sulphide and trace metals that can be toxic to seagrasses (Govers *et al*., 2014a; López-Contreras *et al*., 2021; Rodríguez-Martínez *et al*., 2020). The phenomena of mass Sargassum proliferation from the tropical North Atlantic Ocean is presumably the result of climate change and excess nutrient input (Djakouré *et al*., 2017; Tjong, 2020). Lastly, invasive seagrass species are threatening native species (Christianen *et al*., 2019).

2.2.5 Saliñas

A slightly less studied ecosystem of Bonaire are the salt pans and salt lakes, which are also known as saliñas. Saliñas are semi-enclosed, saltwater bodies which form near the coast and experience salinity shifts from nearly fresh water to hypersaline conditions throughout the year (Jongman *et al*., 2009). The island of Bonaire has a number of extensive saliñas, including five internationally recognized wetland areas that are under the protection of the Ramsar convention.

Bonaire’s saliñas (salt lakes) and bays provide important ecosystem services, including coastal protection, flood control, carbon storage, nutrient and sediment capture and retention, as well as increasing biodiversity by providing unique habitat, such as seagrass beds and mangroves on which many species depend. Saliñas are important areas for many different species of fish, crustaceans and coastal birds, specifically flamingos, terns and sandpipers (Debrot *et al*., 2009). The combination of the visually attractive landscapes and the presence of colourful flamingo populations make the saliñas a popular attraction for tourists. The salt pans and flamingos which are so typical for Bonaire feature in most tourist brochures for the island.

The saliñas are exposed to several local and more global threats, with sea level rise being one of the primary concerns for these coastal ecosystems. Due to erosion and natural succession, many of the saliñas and bays are silted up, which can eventually lead to the death of eelgrass, mangrove and coral. In addition, soil and groundwater contamination and overgrazing by free roaming feral livestock further threatens the health and utility of saliñas (Lagerveld *et al*., 2015). Many of the saliñas and bays of Bonaire are currently threatened by eutrophication and relatively rapid silting and land accretion, causing the water level to drop. The saliñas are also expected to experience stress from the influx of Sargassum, but to a lesser extent than Lac Bay as they are more isolated from the open ocean and the probability of Sargassum influx is smaller. Whether these changes affect bird populations, such as flamingos, remains unclear. A recent study observed an increasing number of dead juvenile flamingos on Bonaire, since 2018, without being able to draw links to the above threats (Amorij *et al*., 2020). Climate change is expected to have an effect on the saliñas, though the extent of this effect is unknown as of yet (Debrot *et al*. 2018). Future research should be conducted to measure the impact of climate change on the saliñas of Bonaire, which if flooded due to sea level rise or storms are likely to be significant.

3 Methodology

The complex objective of this study to assess the environmental, socio-economic and cultural impacts of climate change on Bonaire calls for a comprehensive interdisciplinary approach in which numerous scientific disciplines are combined. This chapter first describes the overall research framework, providing an overview of the biophysical and socio-economic interlinkages in the study. Next, a brief description of the applied methods for the different components of the study is provided.

3.1 Research set-up

Studying the effects of climate change on Bonaire is a complex process with a multitude of interacting effects. To deal with this complexity a framework was developed to connect the different sub-studies into an overarching research topic (see Figure 3-1). The framework provides a schematic pathway of the different steps in which the effects of climate change cause biophysical and socioeconomic impacts, and how these subsequently translate into changes in wellbeing on Bonaire. Different scenarios are simulated, considering distinct climate change pathways for Bonaire. As shown in Figure 3-1, the research framework contains five distinct steps:

1. First, climate change effects are the drivers of change that are examined in this study (Figure 3-1.1). These climate change effects are modelled through emission scenarios as developed by the IPCC and serve to provide input data to model the biophysical and socio-economic effects of climate change on Bonaire. Chapter 4 describes climate change effects on Bonaire, and the subreport “An assessment of the impacts of climate change on coastal inundation on Bonaire” provides further detail.
2. Second, biophysical effects are described in terms of impacts on ecosystems and levels of inundation (Figure 3-1.2). Ecosystem impacts encompass the spatial and quantitative modelling of coral reef health and a qualitative description of effects on other ecosystems. A flooding model was developed to create insight into the effects of sea level rise. Chapter 5 and chapter 6 describe these biophysical effects, and the subreports “Reef degradation and tourism: The macroeconomic costs of climate change on Bonaire” and “An assessment of the impacts of climate change on coastal inundation on Bonaire” provide further detail.
3. Third, outputs from the biophysical were translated into socioeconomic effects, focusing on macroeconomic effects related to changes in tourism arrivals, human health effects, direct safety concerns related to flood risk, and cultural value effects (Figure 3-1.3). These socio-economic effects are described in chapters 7, 8, 9 and 10, with further detail being provided in the subreports on reef degradation and tourism, cultural heritage, the built environment and the report on public health.
4. Fourth, the socio-economic effects in turn can lead to impacts on the general wellbeing of Bonairian citizens, such as impacts on income, food security, human health and safety, social stability and cultural heritage (Figure 3-1.4). These socio-economic effects are described in chapters 7, 8, 9 and 10, with further detail being provided in the subreports on reef degradation and tourism, cultural heritage, the built environment and the report on public health.

5. Fifth, the framework presents several climate change adaptation options, which will be crucial to deal with the consequences of climate change (Figure 3-1.5). These adaptation options are described in chapter 11 and are further detailed in the subreport “Protecting Bonaire against Coastal Flooding”.

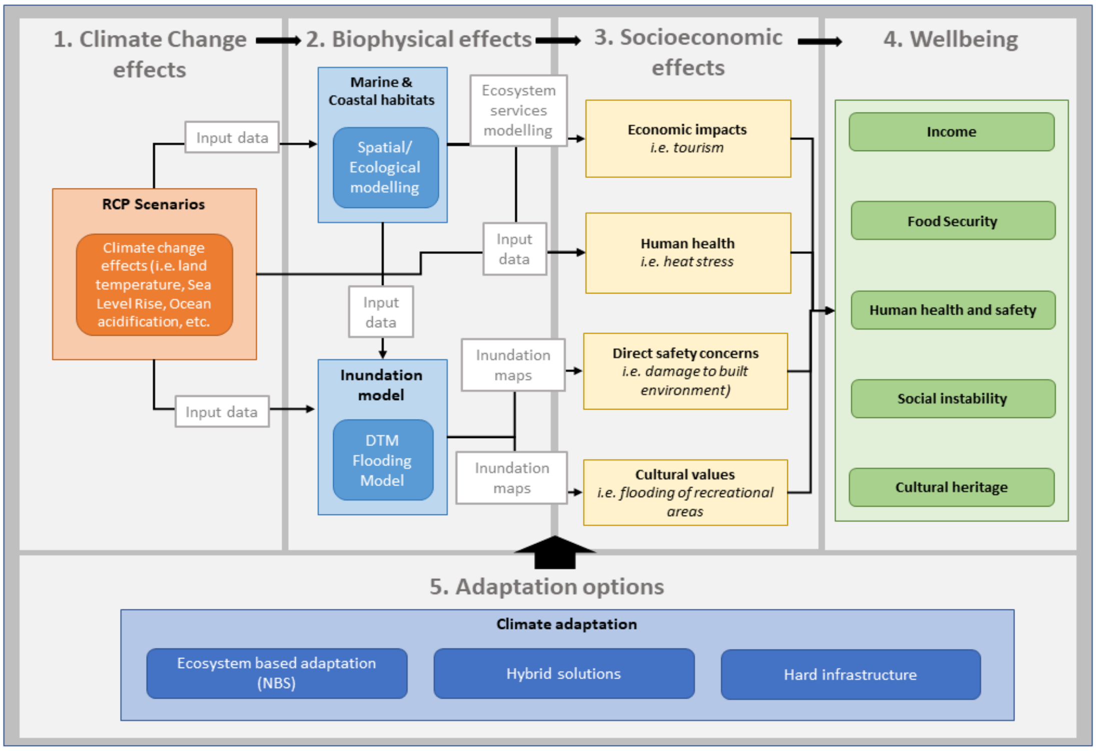


Figure 3-1 Research framework, describing the logic behind all aspects of the study and the interlinkages between these aspects.

3.2 Applied methods

In order to examine the effects of climate change and to provide a comprehensive overview of the drivers, consequences, and potential responses of climate change on Bonaire, a variety of studies have been conducted. The full versions of the six studies comprising this report provide a more detailed description of the applied methodologies and results. This synthesis report includes a short description of applied methods and presents the main results and implications. The titles, authors and applied methodologies of the subset of studies on which this synthesis report is based are listed in Table 3-1 and are briefly described in the sections that follow.

The diversity of disciplines necessitated to provide a holistic overview of the expected impacts and response defences of climate change requires a wide range of applied methodologies. While the biophysical and economic analyses are mostly based on quantitative models (climatic, ecological, inundation, and economic), the latter three parts of the study (cultural heritage, health and the evaluation of adaptation options) are based on qualitative data and rely heavily on local (stakeholder) experiences and expertise. Due to the diverse and complete research approach, this study provides a unique and thorough overview of possible impacts of climate change on human safety, livelihoods and general wellbeing in Bonaire.

Table 3-1 Applied research methods per subset of the study

Research topic	Author	Title	Methodology
Coastal inundation	Dullaart *et al.*, 2022	An assessment of the impacts of climate change on coastal inundation on Bonaire	Digital Elevation Model: FABDEM (Hawker *et al.*, 2022) Flood models: Bathtub & SFINCS model
Coral reefs and economic development	Schep *et al.*, 2022	Reef degradation and tourism: The macroeconomic costs of climate change on Bonaire	Reef analysis: Reef Health Index (RHI) (Kramer *et al.*, 2015) Economic analysis: Green Economic Model (GEM) (Koks & van Zanten, 2015)
Built environment	Koks *et al.*, 2022	The vulnerable future of Bonaire: A direct climate damage assessment of the built environment of Bonaire	Vulnerability analysis: Expert interviews Exposure analysis: Microsoft Bing Maps, OpenStreetMap and neighbourhood sampling
Cultural heritage	van Beukering *et al.*, 2022a	Non-Economic Loss and Damage from Climate Change on Bonaire: An Assessment of the Impacts of Climate Change on Cultural Heritage	Desk research Expert interviews Participatory mapping Social Media analysis
Public health	van Beukering *et al.*, 2022b	Non-Economic Loss and Damage from Climate Change on Bonaire: An Assessment of the Impacts of Climate Change on Public Health	Literature review Expert interviews
Coastal adaptation measures	Tiggeloven *et al.*, 2022	Protecting Bonaire against coastal flooding: a participatory multi-criteria analysis of coastal adaptation options	Multi Criteria Analysis Expert interviews

3.3 Scenario analysis

To analyse the impact of climate change on Bonaire, multiple IPCC and scenarios over time are used. More specifically, the climate change scenarios used, come from the IPCC 6th assessment report. Projected changes in, for example, temperature, precipitation, and sea level rise (SLR) depend on how climate and society are going to change. To this end, the IPCC incorporates both physical and socioeconomic factors into different climatic scenarios in the Shared Socioeconomic Pathway (SSP) - Representative Concentration Pathway (RCP) framework (Van Vuuren & Carter, 2014; O'Neill el al., 2020). SSPs are descriptions of how society may evolve up to the year 2100 and follow societal factors concerning demographics, economic growth, governance and human development. In total, there are five different SSPs that cover a range of possible societal futures. Next to the SSPs, RCPs are more related to the physical change in climate. RCPs are defined as descriptions of how climate may evolve over the rest of the 21st century in a quantitative way. They project future atmospheric concentrations of greenhouse gases and the climate changes they will cause (O'Neill *et al*., 2020).

In the latest climate change projections of the IPCC, five of these scenarios are used to cover a range of possible future development of anthropogenic drivers. All scenarios start in 2015 and go until the end of this century. To investigate a wide range of possible futures for Bonaire, we look at a large set of SSP-RCP scenarios ranging from low-end, to medium to high-end scenarios of the IPCC. As presented in Table 3-2, SSP1-1.9 is the used low-end scenario, followed by SSP2-4.5, SSP5-8.5 and the high-end scenario SSP5-8.5 LC (Low Confidence). To analyse the quality of coral reef degradation, climate scenario SSP3-7.0 is applied. The temporal scope of the four SSP scenarios are the years 2050, 2100 and 2150. Additionally, for the year 2300, a low and high-end scenario are analysed to examine coastal flooding. When examining the effects on public health, no distinction between climate scenarios and time frames has been made, as at this moment it is impossible to distinguish between the predicted effects of different climate scenarios.

Similarly, the section of this report that discusses adaptation measures against coastal flooding does not consider climate scenarios or temporal scales, as it focuses more on desirability and stakeholder preferences than on technical feasibility or protection efficacy against flooding in a particular scenario. Analysing the biophysical effects of climate change has been done through modelling and, hence, quantitative analysis. Similarly, the effects of flooding on the built environment and the effects of coral degradation on Bonaire's economic development is based on modelling. However, to overcome issues of data scarcity, qualitative research in the form of stakeholder consultation was frequently required to supplement quantitative analysis. Qualitative research exclusively was performed to identify the effects of climate change on human health.

Table 3-2 Examined scenarios, temporal scales and applied research methods

	Inundation	Built environment	Coral reefs	Economic development	Cultural heritage	Health	Adaptation
Year	2050 2100 2150 2300	2050 2150	2050	2050	2150	NA	NA
Scenarios	SSP1-1.9 SSP2-4.5 SSP5-8.5 SSP5-8.5 LC	SSP1-1.9 SSP2-4.5 SSP5-8.5 SSP5-8.5 LC	SSP1-1.9 SSP2-4.5 SSP3-7.0 SSP5-8.5	SSP1-1.9 SSP2-4.5 SSP5-8.5 SSP5-8.5LC	SSP1-1.9 SSP5-8.5LC	NA	NA
Research methods	Quantitative	Quantitative and qualitative	Quantitative and qualitative	Quantitative and qualitative	Quantitative and qualitative	Qualitative	Quantitative and qualitative

4 Climate trends

This chapter summarises the physical changes that are expected to occur in Bonaire's climate as a result of climate change. These chosen scenarios for the analysis are introduced in the previous chapter, and include SSP1-1.9, SSP2-4.5 and SSP5-8.5 and correspond to an estimated global mean surface temperature warming at the end of the 21st century of 1.4, 2.7 and 4.4°C, respectively. This is relative to pre-industrial global mean temperatures (IPCC, 2021). Besides the three SSP scenarios, an extra high-end scenario is modelled: SSP5-8.5 Low Confidence. This is the same climate scenario as SSP5-8.5, however, the modelled SLR projections of this scenario includes uncertainty as melting processes of Greenland and Antarctic ice sheets that are not yet fully understood (IPCC, 2021). Due to the inclusion of those ice sheet processes, the deviation in the SLR projection models is large for the SSP5-8.5 LC scenario. Nevertheless, the mean projected SLR in this scenario is the highest compared to the other three modelled scenarios. More detailed information is presented in the study by Dullaart (2022). The following sections will describe how temperature, precipitation, sea level rise and extreme weather events are expected to change under each scenario.

4.1 Temperature

In the Caribbean, extreme temperatures are already occurring at an increased frequency due to climate change (Taylor *et al*., 2020; Stephenson *et al*., 2014). Due to the lack of a multi-year time series of temperature on Bonaire, no trends in temperature change can be assessed with island specific data (Dullaart, 2022). However, on Curaçao, Bonaire's neighbouring island, mean temperature has increased by 0.6°C since 1980 (KNMI, 2021). Furthermore, in all IPCC scenarios by 2100, a temperature increase is expected (Taylor *et al*., 2020). This increase is ranging from 0.83°C to 3.05°C for the least to most extreme scenario with respect to the baseline period 1986-2005 (Taylor *et al*., 2020).

4.2 Precipitation

Currently, there has already been a declining trend in rainfall during the summer months in the Caribbean (IPCC, 2021). However, this trend is not statistically significant at the five percent significance level (Taylor *et al*., 2020; Jones *et al*., 2015). In fact, for Bonaire no significant positive or negative trend in precipitation has been observed so far (KNMI, 2021).

According to Taylor *et al*. (2020), annual precipitation is expected to decrease by 2100 compared to 1986-2005 in all IPCC scenarios. In the Caribbean region this ranges from -0.46% for SSP1-2.6 to -16.95% for SSP5-8.5. Despite the uncertainty for Bonaire specifically and the lack of statistical significance of this negative trend, we follow this projection by Taylor *et al*. (2020) in this study. More research results on this topic is expected from the KNMI.

4.3 Sea level rise

The sea level in the Caribbean is rising at a similar rate (1.8mm/year) as the global rate (1.7mm/year) and has risen by 10.6 cm from 1950 to 2009 (Taylor *et al*., 2020; Palanasamy *et al*., 2015; Torres & Tsimplis, 2013). This means that the SLR around Bonaire and the Caribbean is expected to rise slightly faster than on average around the world (KNMI, 2021). According to the IPCC's scenario pathways, the projected range of SLR for 2081-2100 compared to 1986-2005 for the Caribbean region is between 0.47 (SSP1-1.9) and 0.85 (SSP5-8.5) metres rise in sea level (Akpinar-Elci & Sealy, 2014; Nurse *et al*., 2014). Verweij *et al*. (2020) argue that one of the challenges for Bonaire is the adaptation to SLR.

Table 4-1 summarises the climate trends in terms of temperature, the frequency of heat waves and SLR, and precipitation in all IPCC scenarios (Taylor *et al*., 2020; NASA, 2022).

Table 4-1 Physical changes projected for the Caribbean and Bonaire in the different climate change scenarios (Angeles-Malasapina et al., 2018; Taylor et al., 2020; NASA, 2022)

			2050	2100	2150
		SSP1/RCP1.9	NA	NA	
	Projected **mean temperature** increase (°C) with respect to 1986-2005 (Caribbean) * shows the range of the projections (Taylor *et al*., 2020)	**SSP1/RCP2.6**	**0.86°C** *0.39 - 1.57°C	**0.83°C** *-0.04 - 1.74°C	
		SSP3/RCP6.0	**1.00°C** *0.69 - 1.66°C	**1.85°C** *1.00 - 2.92°C	
		SSP5/RCP8.5	**1.50°C** *0.94 - 2.23	**3.05°C** *2.10 - 4.22°C	
		SSP1/RCP1.9	NA	NA	
	Projected mean **precipitation** change (%) with respect to 1986-2005 (Caribbean)	**SSP1/RCP2.6**	-0.09	-0.46	
		SSP3/RCP6.0	-2.42	-6.91	
		SSP5/RCP8.5	-6.27	-16.95	
		SSP1/RCP1.9	0.23	0.47	0.70
	Projected **sea level rise** (m) relative to 1995-2014 (Bonaire)	**SSP1/RCP2.6**	0.24	0.51	0.78
		SSP2/RCP4.5	0.25	0.64	1.05
		SSP5/RCP8.5	0.27	0.85	1.45

4.4 Extreme weather events

4.4.1 Heat waves and drought

Climate change has increased the frequency, duration, and intensity of “warm and hot days and nights” in the Caribbean between 1961 and 2010 (Taylor *et al*., 2020, p.99). Global warming projections show that most of the Caribbean will become drier, and that agricultural and ecological droughts will become more common and severe (Hersbach *et al*., 2020; Debrot *et al*., 2018; IPCC, 2021).

4.4.2 Tropical cyclones

The IPCC has expressed low confidence in a global increase in tropical cyclone frequency and intensity (Stephenson & Jones, 2017). Bonaire lies on the Atlantic hurricane belt’s southern border and experiences tropical cyclones at a much lower frequency than the Dutch Windward Islands (Meteorological Department Curaçao, n.d.). Historically, the ABC-islands are considerably damaged by hurricanes about every 100 years, due to heavy rains and rough seas that can cause flooding for several days (Meteorological Service Netherlands Antilles and Aruba, 2010).

4.4.3 Storms

Storms are predicted to worsen with climate change. Stronger storms, in combination with Bonaire’s coral reef degradation, can likely trigger an increase in storm-related damages on Bonaire (Dutch Caribbean Nature Alliance, 2019). Additionally, flooding is expected to increase in frequency and intensity in the Caribbean (CDC, n.d)

5 Impacts on coral reefs

5.1 Applied methods to analyse coral reef quality

To study the effects of climate change on the quality of coral reefs around Bonaire, we utilised the Reef Health Index (RHI) (Kramer *et al*., 2015) as an indicator of coral reef quality that could be modelled under climate change scenarios. The Reef Health Index (RHI) is employed to reflect the current health of the coral reefs (Kramer *et al*., 2015). This index was developed to assess the state of the Mesoamerican Reef in the Caribbean (Diaz-Perez *et al*., 2016). The coral reefs of Bonaire exhibit similar characteristics in coral species and depth as Mesoamerican reefs, making the RHI a valid indicator to proxy the state of Bonairian reefs (Meesters *et al*., 2019). As shown in Figure 5-1, the RHI consists of four key health indicators: (1) coral cover, (2) macroalgae cover, (3) biomass of key herbivorous fish, and (4) biomass of key commercial fish. An RHI ranging between 1.0-1.8 indicates a reef in “Critical” state, 1.8-2.6 indicates a “Poor” state, 2.6-3.4 equals a “Fair” state, 3.4-4.2 “Good,” and 4.2 – 5.0 is seen as “Very Good” (Kramer *et al*. 2015). A baseline for RHI on 115 transect zones along the leeward side was developed by Meesters (2020) with an average RHI of 2.9, which served as the base for future projections for RHI at these transect zones (Figure 5-2). Note that there are differences in quality between the shallow reef (5m) and the deep reef (10m), with transect points along the shallow reef having a higher frequency of poor-quality sites. The island’s windward side is rarely used for tourism purposes and was, therefore, less economically relevant in the context of this study.

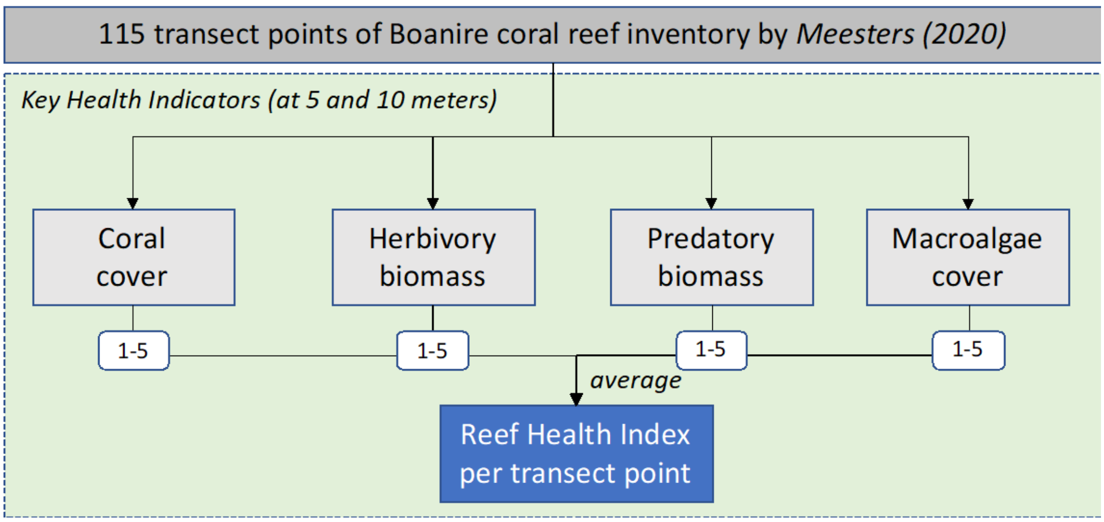


Figure 5-1 Overview of established social carrying capacity using key health indicators obtained from Meesters (2020) extrapolated inventory of Zanke & DeFroe (2017)

To predict future changes in the RHI of the 115 transect points by 2050, an ecological module was constructed based on the Green Economic Model (GEM) model by Koks & Van Zanten (2015), a macroeconomic Input-Output model with an ecological module. The ecological module reflects the state of the coral reef ecosystems of Bonaire. The health of these marine systems is affected by local and global stressors and ecosystem properties, which ultimately affect dive tourism demand. Key reef health indicators are impacted by global climate stressors through the external effects of algal blooms, ocean acidification, and coral bleaching. Storm damage is excluded as an effect due to insufficient data and a high degree of uncertainty on the consequences of this effect. The magnitude of these global stressors depends on the CO_2eq concentrations, Sea Surface Temperature (SST), and Air Temperature (AT) levels of the climate scenarios. The ecological module directly links any changes in key health indicators in the reef ecosystem to the quality of the available dive spots on Bonaire. When a transect zone reaches a final RHI below 1.8 and its state is considered "Critical", it is assumed that the dive site becomes unattractive for scuba diving. As such, the degradation of local coral reefs reduces the available amount of dive sites, thus decreasing the supply of dives for tourists.

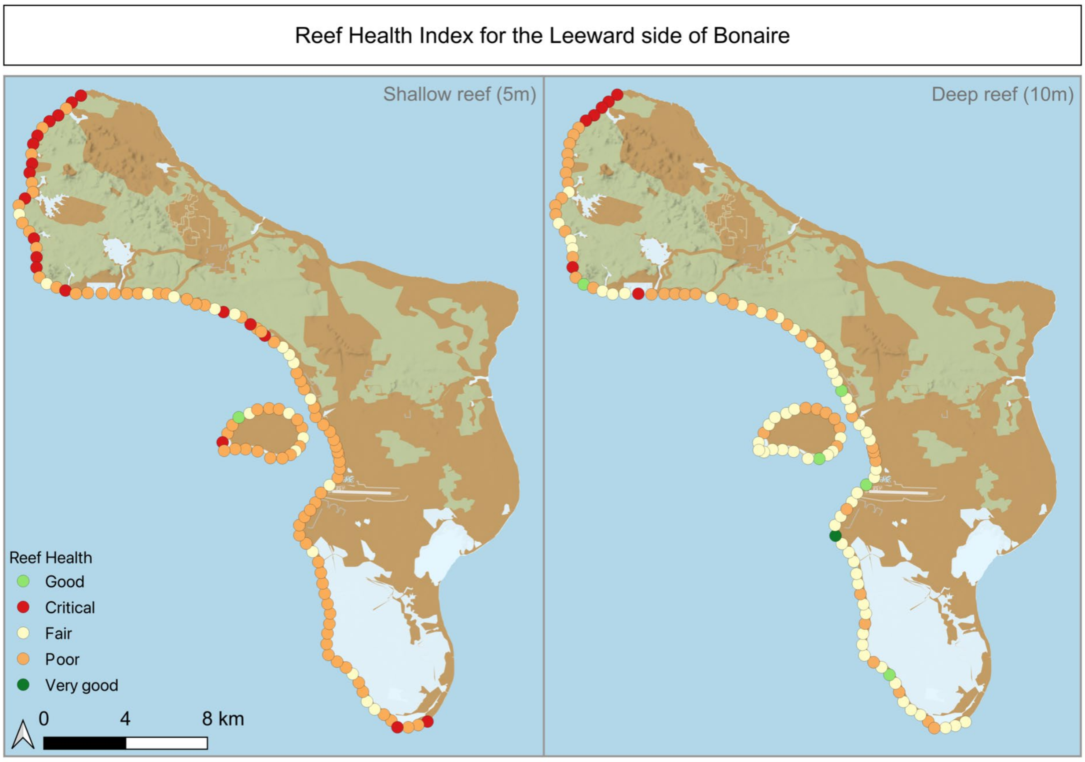


Figure 5-2 Maps of the RHI per transect zone on the Leeward side of Bonaire. On the left, the RHI of the shallow reef (5 meters) is provided. The right map shows the RHI of the deep reef (10 meters). Reproduced from Zanke & De Froe (2017).

5.2 Impacts on coral reef quality

The impacts of climate change on the coral reefs of Bonaire were studied by modelling the Reef Health Index of 115 transect zones for different climate change scenarios. The results indicated that the coral reefs were on average in a "Fair state" in 2017. However, the marine ecosystems were still recovering from hurricane "Omar" in 2008 and a severe bleaching event in 2010 (Steneck, 2019). Next, a decrease in reef health across all but one climate scenario was found (Figure 5-3). In the SSP1-1.9 scenario, the number of quality dive sites is expected to remain at 86 by 2050. A rise in algae cover is offset by a moderate increase in herbivory fish populations and coral cover, which increases the average RHI score of the marine ecosystem to 3.18. Conversely, scenarios SSP2-4.5 and SSP3-7.0 result in significant reef degradation before 2050. In scenario SSP2-4.5, mean live coral cover falls to 7.4%, while total fish stock is expected to decrease from 463 to 262 tonnes. Ultimately, the number of quality dive spots drops from 86 to 72 (Figure 5-4). Similarly, in SSP3-7.0 mean live coral falls to 3.9%, while the biomass of the total fish stock decreases from 463 tonnes to 156 tonnes by 2050. In addition, algae cover grew to its maximum of 82.2% due to steadily rising temperatures. As a result, the number of quality dive sites drops from 86 to 51. Finally, scenario SSP5-8.5 displays the most severe decline. The average RHI score of a transect point drops from 3.02 to 1.47, indicating that the coral reefs are in a "Critical" state. Mean live coral cover falls to 0% by 2050, and macroalgae cover grows exponentially. However, the leeward side of the island still provides 12 quality dive sites out of the initial 86 as there are fish populations present, although small in size (94 tonnes).

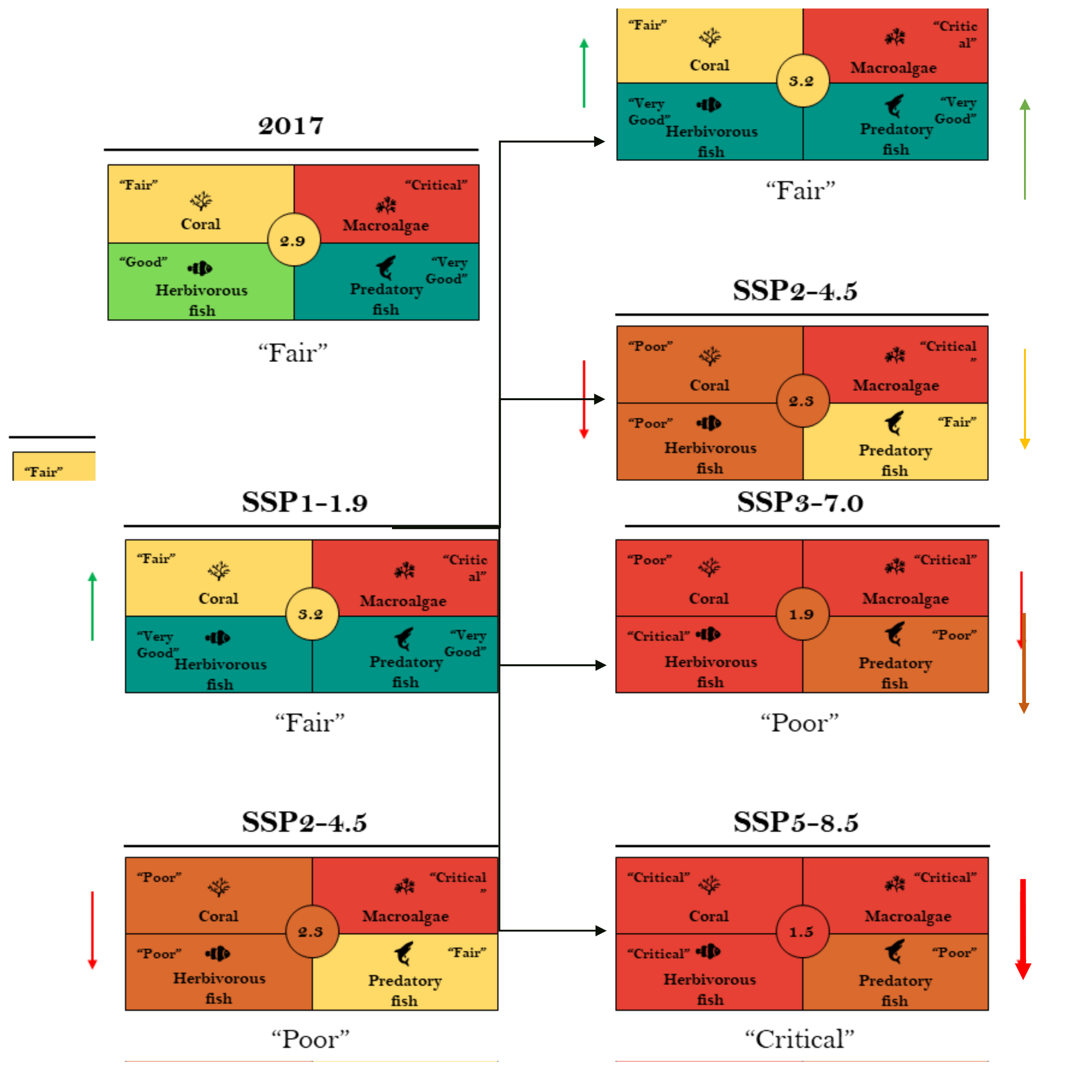


Figure 5-3 Overview of average RHI under the climate scenarios, compared with the 2017 baseline. All climate scenarios, except from SSP1-1.9, show a declining trend in average RHI by 2050 due to increases in AT, SST, and CO2

5.3 Coral reef outlook beyond 2050

Although the model only runs until 2050, it is vital to emphasise that coral degradation does not stop beyond this threshold. It is hard to project the effects of climate change and local stressors on the coral reefs surrounding Bonaire specifically, but based on IPCC projections we can hypothesise about the future of the reefs. In the IPCC chapter "Changing Ocean, Marine Ecosystems, and Dependent Communities" (Bindoff *et al.*, 2019), projections for coral reef degradation up to 2100 are provided. These projections unambiguously indicate that warm water coral reefs are expected to experience very high risks of degradation even if global warming is limited to 1.5 degrees Celsius (Bindoff *et al.*, 2019). Of the potential shared socioeconomic pathways, only under SSP1-1.9 will global warming be limited to approximately 1.4 degrees Celsius by 2050 and decline beyond this point. Consequently, unless society manages to reach net zero emission around 2050, it is very likely that Bonaire's coral reefs will degrade beyond 2050.

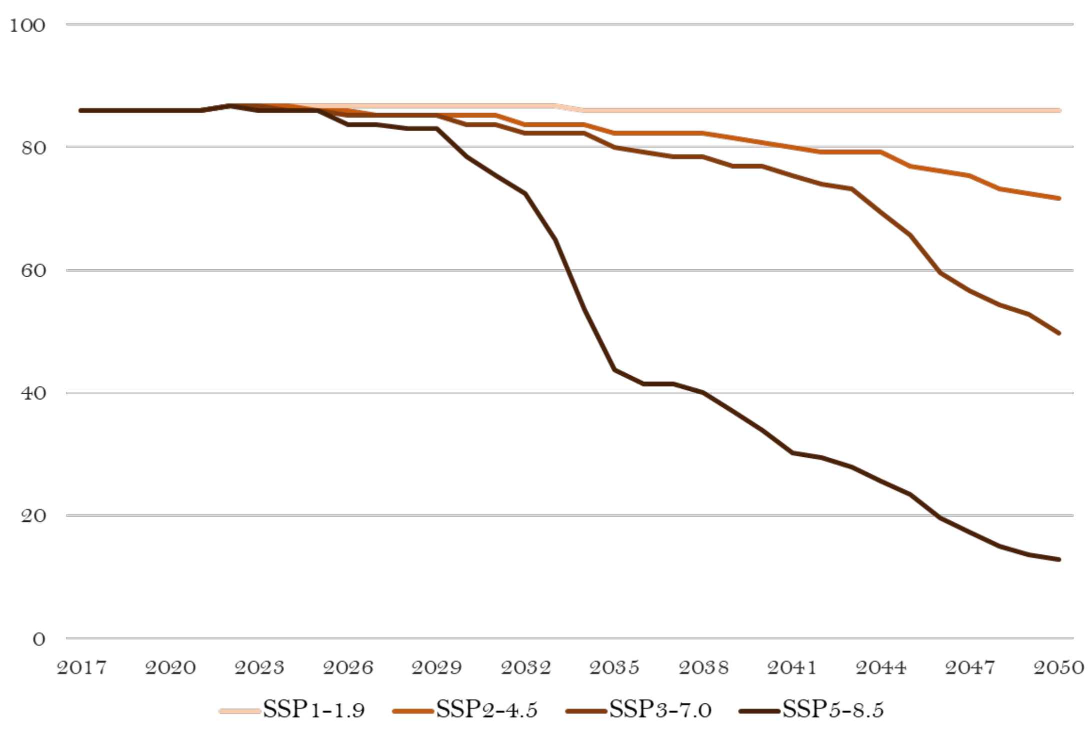


Figure 5-4 The number of quality diving sites (86 at start in 2017) with a RHI > 1.8, between 2017-2050.

6 Coastal inundation hazards

6.1 Applied methods to analyse coastal flood hazard

To assess the coastal flood hazard on Bonaire under current and future climate conditions, two inundation models will be used. First, a static inundation model, also referred to as bathtub model, is used to simulate the permanent inundation of Bonaire due to SLR, using different SLR projections. For this study, we use a selection of the available SLR projections from the IPCC, which are presented in Table 6-1. The SSP5-8.5 low confidence (LC) scenario takes into account uncertain melting processes of the Greenland and Antarctic ice sheets. In addition to the SLR projections, information about the land surface elevation is required. The digital elevation model (DEM) that we use is called FABDEM (Hawker *et al*., 2022), and is based on the global 30-metre resolution Copernicus DEM (GLO-30) with forests and buildings removed. A much more detailed Lidar DEM, such as the Algemeen Hoogtebestand Nederland (AHN) that is available for European Netherlands, would have been the preferred option but is not available for Bonaire. An accurate DEM is essential for the inundation results and associated impacts.

Table 6-1 Mean projections of SLR around Bonaire for different SSP-RCP scenarios and different temporal scales (IPCC, 2021). Values between brackets indicate the 17th - 83rd percentile range

SLR (m)	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP5-8.5	SSP5-8.5LC
2050	0.23 (0.12-0.36)	0.24 (0.11-0.37)	0.25 (0.13-0.38)	0.27 (0.15-0.41)	0.28 (0.15-0.49)
2100	0.47 (0.19-0.77)	0.51 (0.25-0.82)	0.64 (0.36-0.98)	0.85 (0.56-1.22)	0.98 (0.55-1.74)
2150	0.70 (0.25-1.20)	0.78 (0.33-1.30)	1.05 (0.55-1.65)	1.45 (0.87-2.19)	2.19 (0.87-5.37)
2300	NA	NA	NA	NA	4.05 (2.2-5.9)

Second, we use a dynamic inundation model to assess the coastal flood hazard under current and future climate conditions. This model is called Super-Fast Inundation of Coasts (SFINCS) and requires input data on the total water level (TWL) over time (Leijnse *et al*, 2021). Information about storm surges and tidal levels, together referred to as the storm tide level, is taken from the COAST-RP dataset (Dullaart *et al*., 2021). This dataset contains several return periods (RPs) of storm tide levels. Due to a lack of historical data, the 1-in-100 year storm tide level is used to assess coastal flooding due to a storm event. Around Bonaire, the contribution of waves to the TWL is relatively large due to the steep coastal shelf (Pugh *et al*., 2007). Therefore, it is important to take waves into account when assessing the coastal flood hazard on Bonaire. To this end, we use hourly time series of significant wave height of wind waves and swell from the ERA5 global climate reanalysis (1979-present) (Hersbach *et al*, 2018).

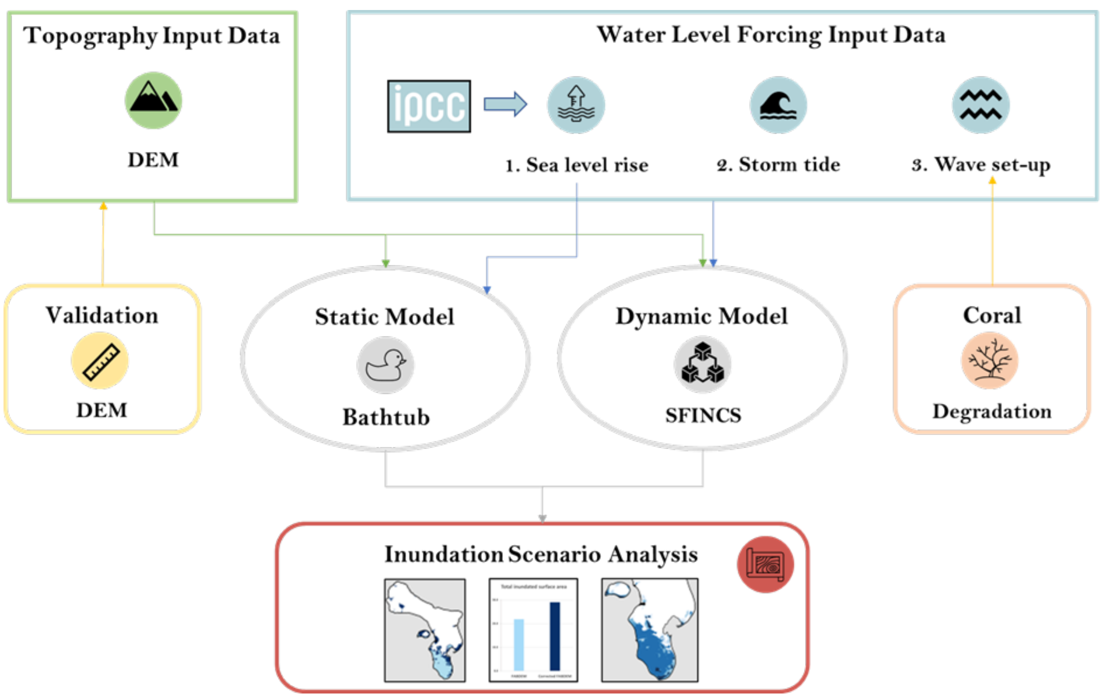


Figure 6-1 Methodological framework of the coastal flood hazard assessment

Overall, climate change is expected to affect the coastal flood hazard of Bonaire in multiple ways. First, SLR will result in more frequent coastal flooding. Also, certain areas will become permanently inundated.

Second, changes in the frequency and intensity of storms can alter the occurrence of coastal flood hazards, although this effect comes with a large level of uncertainty. Overall, tropical cyclones (TCs) are expected to occur less often but the most intense TCs (category 4-5) are expected to increase in frequency. Because the effect of SLR on the coastal flood hazard is expected to be significantly larger than changes in storminess (Vousdoukas *et al*, 2018), we assume that the 1-in-100 year TWL RP remains constant towards the future.

Third, due to SLR, warming oceans, and ocean acidification, coral reefs degrade (Wilkinson, 1996; Hoegh-Guldberg, 2011). Coral reefs currently function as a wave breaker and thus reduce the total water level under storm conditions. To assess how the absence of coral reefs potentially increases the coastal flood hazard, an extra simulation is performed using SFINCS in which we increase the wave set-up, replicating the absence of a healthy reef. The projected SLR in this extra simulation is based on SSP2-4.5 (2050).

6.2 Permanent inundation due to SLR (Bathtub model)

Figure 6-2, 6-3, and 6-4 illustrate the coastline of Bonaire in 2050, 2100, and 2150, respectively, for the following SSP-RCP scenarios: SSP1-1.9, SSP5-8.5 and SSP5-8.5 LC. These scenarios were chosen because they show the widest range of possible future scenarios. What stands out for 2050 is that the size of the permanently inundated area is almost similar for all three SSP scenarios. This is a direct result of the very small difference in projected SLR for 2050 between SSP1-1.9 of 0.23 m and 0.28 m under SSP5-8.5LC. For 2100 the expected SLR is 0,47 m under SSP1-1.9 and 0,98 m under SSP5-8.5LC. Although under these scenarios permanent inundation is already substantial by 2100, the total area expands a lot when looking further to 2150 and beyond. The expected SLR in 2150 ranges from 0.70 (SSP1-1.9) to 2.19 metres (SSP5-8.5 LC). The inundation maps for 2150 depict permanent inundation and therefore exclude the possible impacts of storms that can temporarily elevate the water level. First, in the low-end SSP1-1.9 scenario, the effect of SLR is most impactful in the most southern part of the island and Klein Bonaire. Then, looking at the SSP5-8.5 projection, the difference in flood extent is relatively small. The coastline extends north- and eastwards from the saliñas again, also permanently flooding the southern part of Belnem. A visual representation of Bonaire's futurecoastlines under different climate scenarios in 2150 can be found in Appendix A. Other urban areas, such as Kralendijk and the airport, will not be permanently flooded, with few exceptions in Belnem, by SLR under the high-end SSP5-8.5 scenario. Finally, the permanently inundated area is substantially larger under the SSP5-8.5 LC Scenario. For example, large parts of Klein Bonaire are permanently flooded, shrinking the island to half of its current size. However, the most important difference with the other scenarios is the large inundated area around Kralendijk and the airport. In the SSP5-8.5 LC scenario, SLR exceeds the lowest point of the seawall directly on the coast of Kralendijk. This causes the lower parts of Kralendijk, directly behind the seawall, to flood. For 2300, two low confidence SLR projections are available: SSP1-2.6 LC (1.05 m) and SSP5-8.5 LC (4.05 m). Under the high-end scenario, the coastline will move far inland. Most importantly, almost all of the city of Kralendijk will be flooded as the coastline moves 2 km inland. Most of Belnem and Klein Bonaire will be permanently inundated as well.

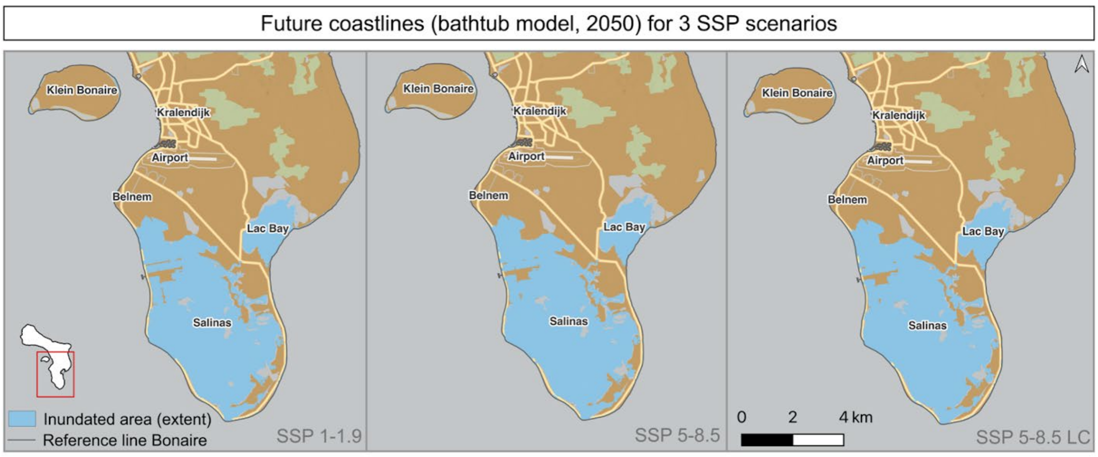


Figure 6-2 Inundation map illustrating the future coastline of Bonaire in 2050 under SSP1-1.9, SSP5-8.5 and SSP5-8.5 LC.

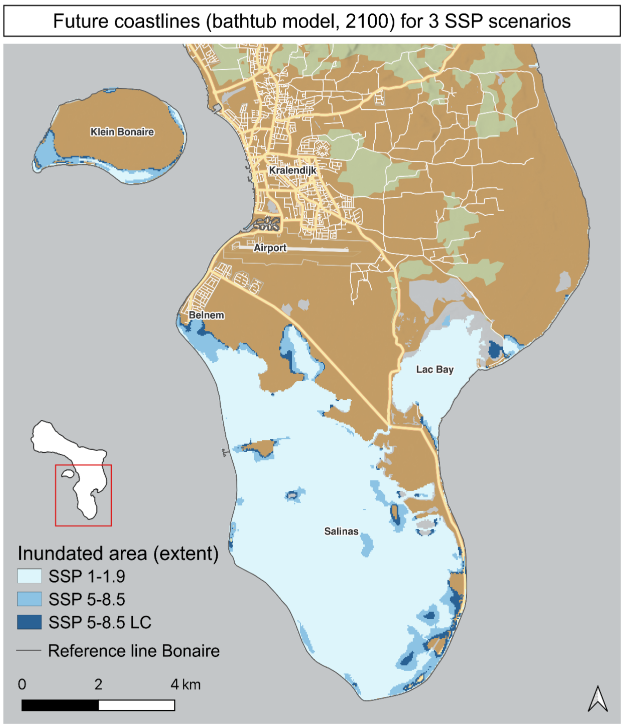


Figure 6-3 Inundation map illustrating the future coastline of Bonaire in 2100 under SSP1-1.9, SSP5-8.5 and SSP5-8.5 LC

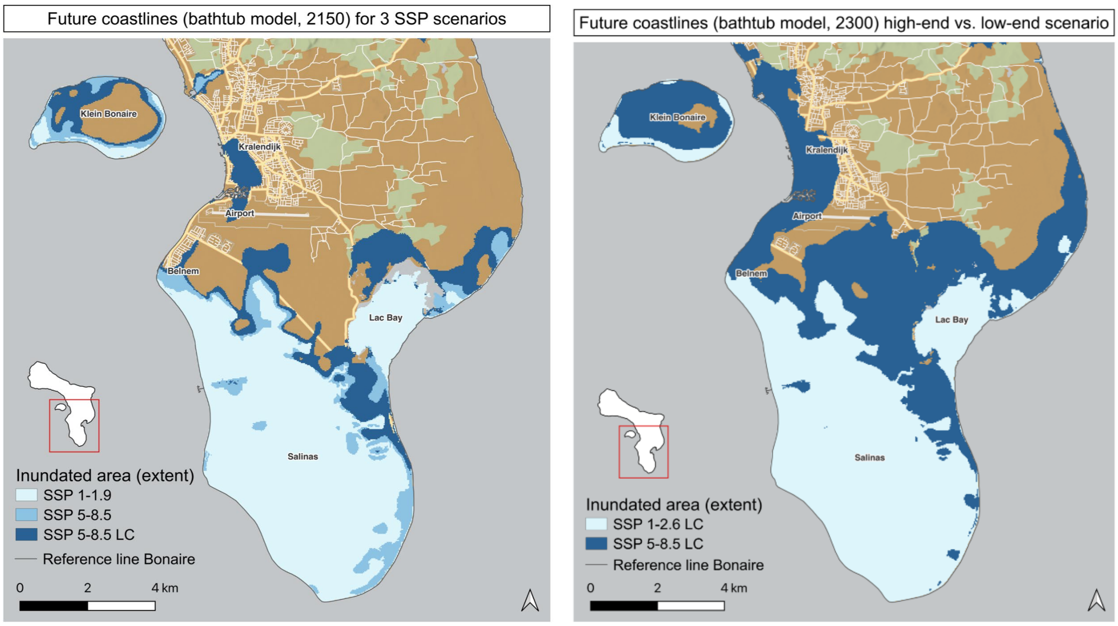


Figure 6-4 Inundation map illustrating the future coastline of Bonaire in 2150 (left) and 2300 (right) under SSP1-1.9, SSP5-8.5 and SSP5-8.5 LC

6.3 Coastal flood hazard: inundation due to storms and SLR (SFINCS model)

The results in this paragraph take into account both SLR and a storm that happens once every 100 years (RP100). Strong winds and low air pressure in such a storm causes storm surge and high waves, thereby further elevating the total water level. To indicate the difference in inundation between the SSP scenarios and the temporal scale, the total inundated surface area is calculated and presented in Figure 6-5. The calculations exclude the surface area of the saliña and the mangroves of Lac Bay, as this is already permanently inundated by SLR alone. The climate scenarios are divided into the three main temporal classes: 2050, 2100 and 2150. Figure 6-5 shows that the total inundated surface area (km2) in 2050 only slightly differs across SSP scenarios, but a broader distinction in flood extent is observable at the end of this century and even more pronounced differences in 2150. Comparing the low-end and high-end LC scenarios in 2150, inundated surface area more than doubles as the total flood area ranges from 15 to 32 km2. The saliñas and mangroves are excluded from the total inundated surface area because these areas are already underwater. Nevertheless, the characteristics and, hence, the services provided by these ecosystems may change due to permanent inundation and coastal flooding.

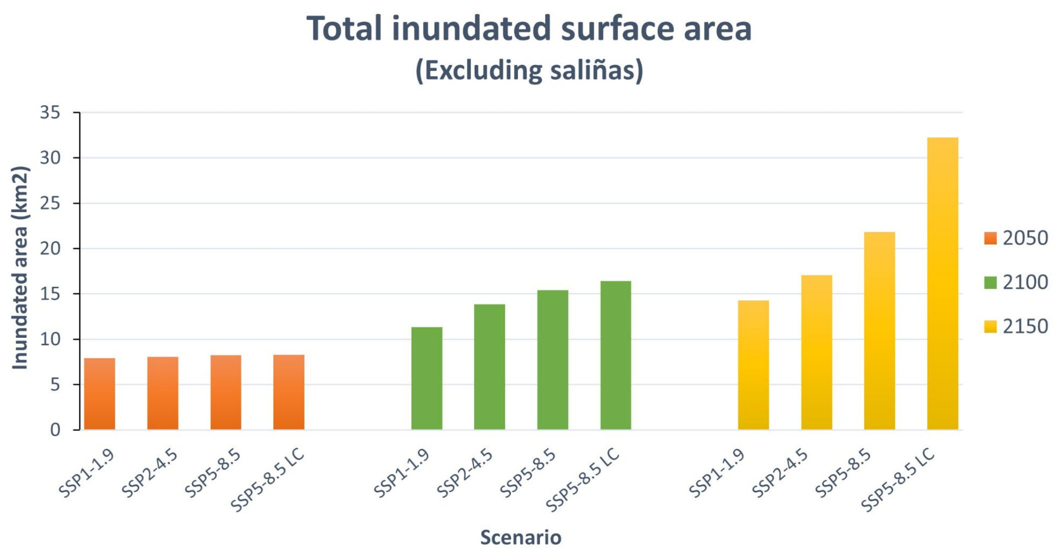


Figure 6-5 Histogram showing the SFINCS simulations total inundated surface area (excluding saliñas and mangroves) of all scenarios is 2050, 2100 and 2150.

In Figure 6-6, the dynamic SFINCS simulations under the low- and high-end LC scenario for 2050, 2100 and 2150 are visualised by means of inundation maps. The visual representation of inundation extent under two climate scenarios in 2300 is presented in Appendix B. It is noticeable that differences in flood extent across climate scenario SSP1-1.9 and SSP5-8.5LC appear to be small for 2050 but become more extreme for the years 2100, 2150 and 2300.

When zooming in on Kralendijk, the scenarios SSP2-4.5 and SSP5-8.5 display the most notable local variances in flooding. This is due to the fact that in the latter simulation, parts of Kralendijk are also flooded. Furthermore, larger areas around Lac Bay and on

Klein Bonaire are predicted to flood. Moreover, in the most extreme SSP5-8.5 LC scenario, substantially greater areas of Kralendijk are expected to be flooded. The same applies to the airport, which in 2150 is inundated in the most extreme scenario. Lastly, in comparison to the first three scenarios, significantly large parts of Belnem, Lac Bay and Klein Bonaire are predicted to flood in the SSP5-8.5 LC scenario. This, in combination with the deep inundation depth, make this a potentially destructive scenario.

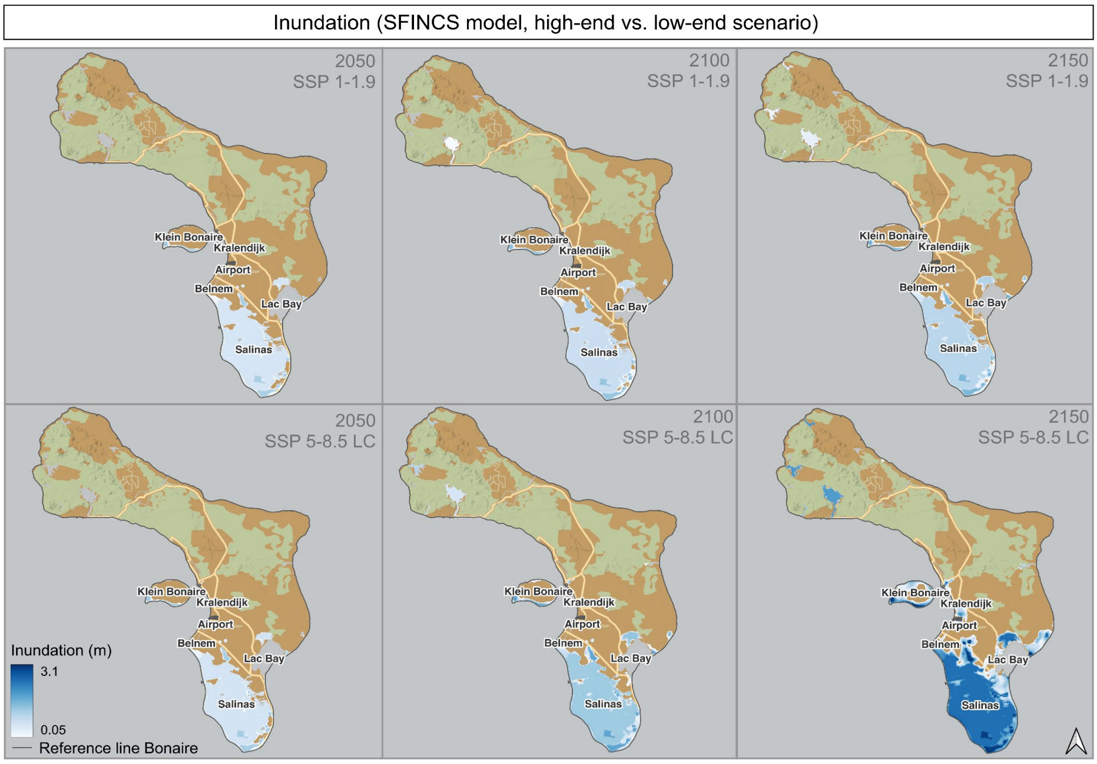


Figure 6-6 Inundation map illustrating flood extent on Bonaire in 2050, 2100 and 2150 under SSP1-1.9, SSP5-8.5 and SSP5-8.5 LC

Figure 6-8 shows the inundation difference under storm conditions (RP100) between a healthy and degraded coral reef under SSP2-4.5 (2050). According to a case study on the Seychelles (Sheppard *et al.*, 2005) the wind set-up increases with 80% on average when a coral reef completely degrades. The total inundated surface area, excluding the saliñas, increases with 41%, from 8.0 to 11.3 km2. Inundation depth increases with an average of approximately 0.24m, with a larger increase directly on the coastline. Therefore, when looking into the effect of SLR on Bonaire the degradation of coral reefs should be taken into account.

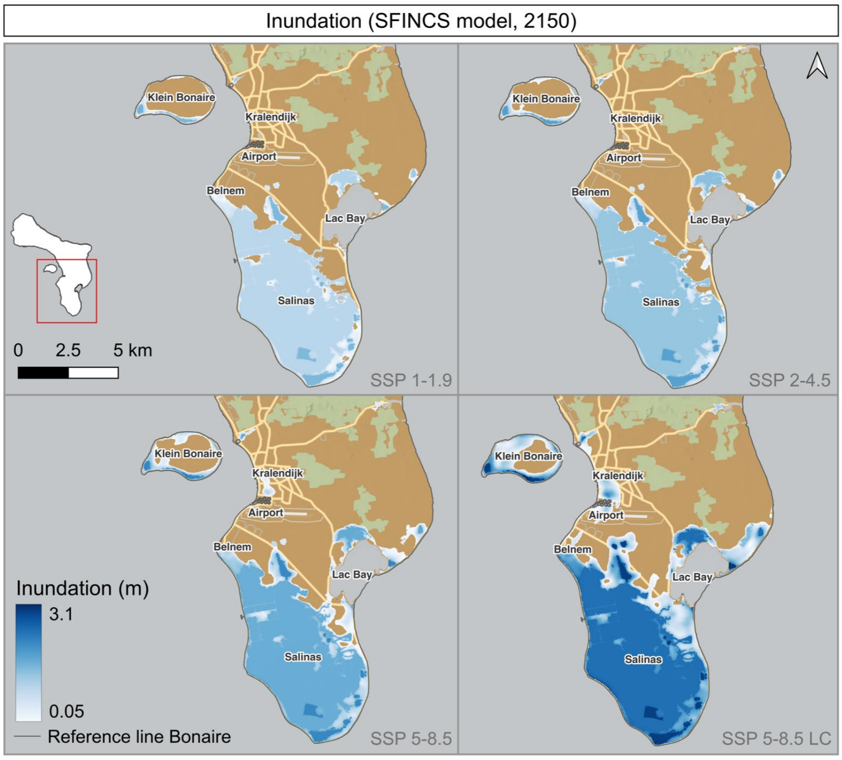


Figure 6-7 Inundation maps of all modelled SSP-RCP scenarios in 2150: SSP1-1.9, SSP2-4.5, SSP5-8.5 and SSP5-8.5 LC, including the 1 in 100-year storm tide and wave set-up RP

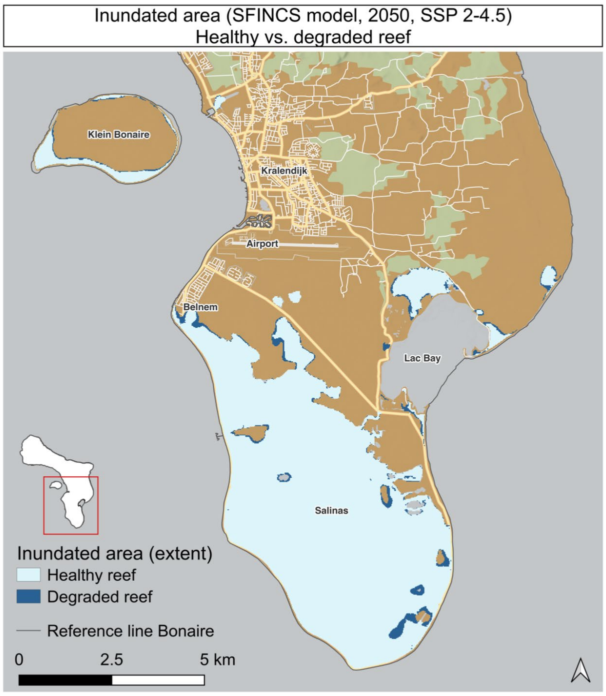


Figure 6-8 The Inundation map illustrates the difference in flood extent between a healthy and degraded reef for scenario SSP2-4.5 in 2050, including the 1 in 100-year RP

6.4 DEM validation

The DEM is a crucial model input in estimating the potential future inundation on Bonaire. The FABDEM used in the model simulations is validated using two different approaches: field measurements and elevation comparisons with an alternative DEM.

6.4.1 Self-retrieved field measurements

The first approach is based on field elevation measurements, which have been performed on the seawall in Kralendijk, since the seawall is a structure with a vertical slope angle structure directly on the coastline. The height of the seawall was measured from the water level to the ground surface, whereafter all measurements were corrected for the tides of the measurement day, May 10th, 2022 (Tide schedule in Bonaire, 2022). The 11 self-retrieved measurements were complemented by five elevation observations provided by Geomaat Caribe B.V. (2022), a Bonairian surveyor company. The field observations showed a substantially large deviation with the FABDEM used in the simulation; all 16 observation points are lower than the FABDEM elevation height, with an average overestimation of the FABDEM of 1.2 metres. Despite the fact that the assumption of a general 1.2 m overestimation by the FABDEM is based on a small number of observations, which have only been conducted in Kralendijk and near the airport, limiting the added-value of the observations, it provides an indication of the FABDEM's uncertainty and inaccuracy in estimating the flood extent. Therefore, it is possible that the inundation maps present an underestimation of the real flood extent. It should furthermore be noted that the measured differences between the FABDEM and land elevation measures is large compared to the high-end SLR projections in 2150 (1.45 m; SSP5-8.5LC).

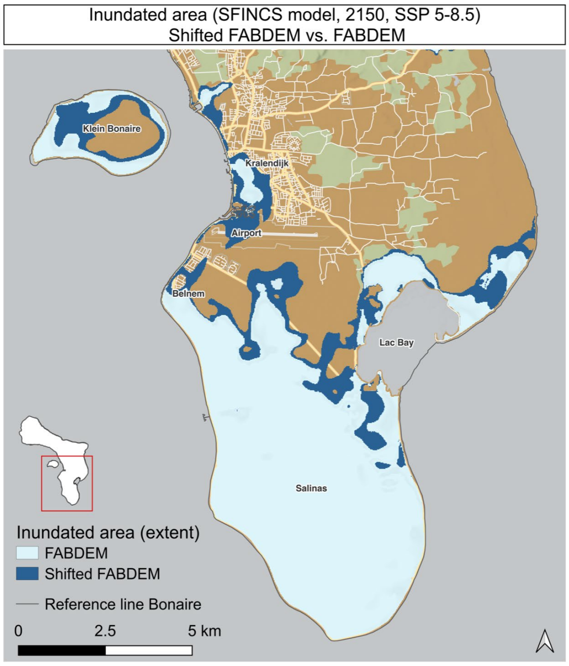


Figure 6-9 Inundation map illustrating the difference in flood extent between the FABDEM and the shifted FABDEM for scenario SSP5-8.5 in 2150, including the 1 in 100-year storm tide and wave set-up RP

The comparison between the shifted DEM and the FABDEM, for scenario SSP5-8.5 in 2150, is portrayed in Figure 6-9. As a consequence of the DEM correction factor of -1.2m, flood extent increased with 53%, with the saliñas excluded. This large increase in the flood extent can be seen in all southern locations, but most significantly around Kralendijk and the airport.

6.4.2 FABDEM vs COASTALDEM

The second method for validating the DEM accuracy involves comparing the FABDEM with a different DEM, named CoastalDEM (Kulp & Strauss, 2018). The CoastalDEM has a similar resolution as the FABDEM of 30 by 30 metres, which means that both DEMs have a coarse resolution for applying it in a local inundation model, which can result in significant inaccuracies. With the CoastalDEM as topographic input data, an additional SFINCS simulation was conducted for the high-end SSP5-8.5 scenario in 2150. Figure 6-10 shows the difference in flood extent between the CoastalDEM (dark blue) and the FABDEM (red) for the high-end SSP5-8.5 scenario in 2150. The light blue colour indicates inundation in both DEMs and demonstrates that both are quite similar when looking at the flooded area. In numbers, the total inundated surface area is 4.8% higher for the FABDEM (Figure 6-10). Especially around Lac Bay and Belnem, more inundation is projected by the FABDEM. On the other hand, the CoastalDEM projects more inundation directly on the coastlines. Overall, the flood maps based on FABDEM and CoastalDEM are very similar. However, these similarities do not necessarily confirm the accuracy of the DEMs because of their low spatial resolution. Although the FABDEM remains suboptimal, it appears the best available DEM for this study.

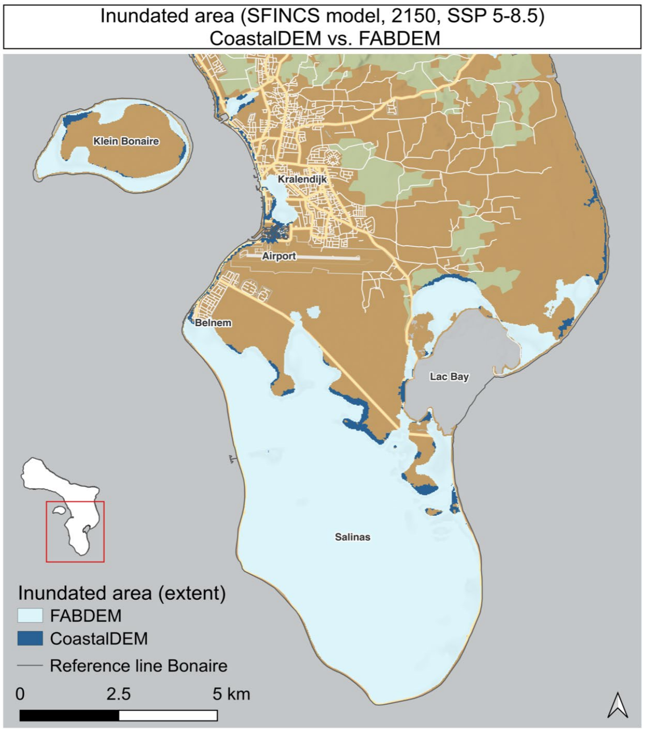


Figure 6-10 Inundation map illustrating the difference in flood extent between the FABDEM the CoastalDEM for scenario SSP5-8.5 in 2150, including the 1 in 100-year storm tide and wave set-up RP

7 Impacts on the built environment

7.1 Applied methods to analyze impact on the built environment

We aim 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 specifically. To assess the impact of coastal flooding to Bonaire's built environment, 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). Due to the difficulty of assessing the lost value of houses due to permanent inundation (i.e. no exact information is available about the buildings that might be affected by permanent inundation), the economic impacts on the built environment due to changing coastlines are not included in the analysis and only briefly described in Section 7.2. As such, the damage estimates in this section could be interpreted as a lower bound estimate of the impacts of climate change.

To identify the coastal hazard, we use the coastal inundation information 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 Low Confidence), modelled using the dynamic SFINCS model and the original FABDEM (see Section 6.3).

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). The value of each sub-categorized building type is based on one of the following three sources: the Rider Levett Bucknall (RLB, 2021) report; the BCQS international (2020) report; and a neighbourhood sampling method for residential buildings. In the neighbourhood sampling method, neighbourhoods are classified into four categories with an associated value for the built environment. This method is newly introduced to produce accurate local data on building values to overcome data scarcity.

Similar to buildings, critical infrastructure is classified into different categories. These categories are developed based on consultations of the local experts and knowledge gained during fieldwork. 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.

To identify the vulnerability per asset, a classification is made based on building height. The buildings are classified using the earlier described neighbourhood sampling, as no detailed data was available. A vulnerability curve is created for each building type, which shows how much an asset or network feature will be damaged by a specific hazard of a certain intensity (i.e. the level of damage for a certain flood depth). Furthermore, this study evaluates the road network's connectivity. Roads that are cut off from the network by flooding 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. The combination of buildings and critical infrastructure damages provides a more complete overview of the expected direct impacts (Garschagen *et al*., 2016).

7.2 Impact of storm inundation on buildings

As presented in Table 7-1, 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 4.3% higher than the expected costs related to climate scenario SSP 1-1.9. This is due to the fact that in 2050 the difference between the various climate scenarios is still limited (see also section 6.3). On Bonaire, only a few buildings are located directly on the (southern) coast since building along coastlines is prohibited, with few exceptions. 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.

Table 7-1 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	23.11
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

When extending the time factor to 2150 for each scenario, much more prominent impacts associated with the different climate projections are found as the extent and intensity of the flood hazard substantially increase. The enlarged inundated area translates into higher flood damages, as indicated in Table 7-1. 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. Therefore, this paper only looks at the influence of future climate change and does not consider a differently structured built environment. 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 monetary damages associated with the different climate scenarios have been estimated for 2150, expressed in present day values. Table 7-1 indicates that whereas expected damages in 2150 SSP 1-1.9 account for 23.11 USDm, these costs are expected to be almost three times as much (229.7% increase in damage costs) in the SSP 5-8.5 scenario (76.2 USDm). Since Kralendijk, a densely built-up area, will significantly flood under climate scenario SSP5-8.5 LC, the number of buildings hit and total expected damage (USDm) increases significantly, with 1655 buildings hit, resulting in expected total damages of 316.8 USDm.

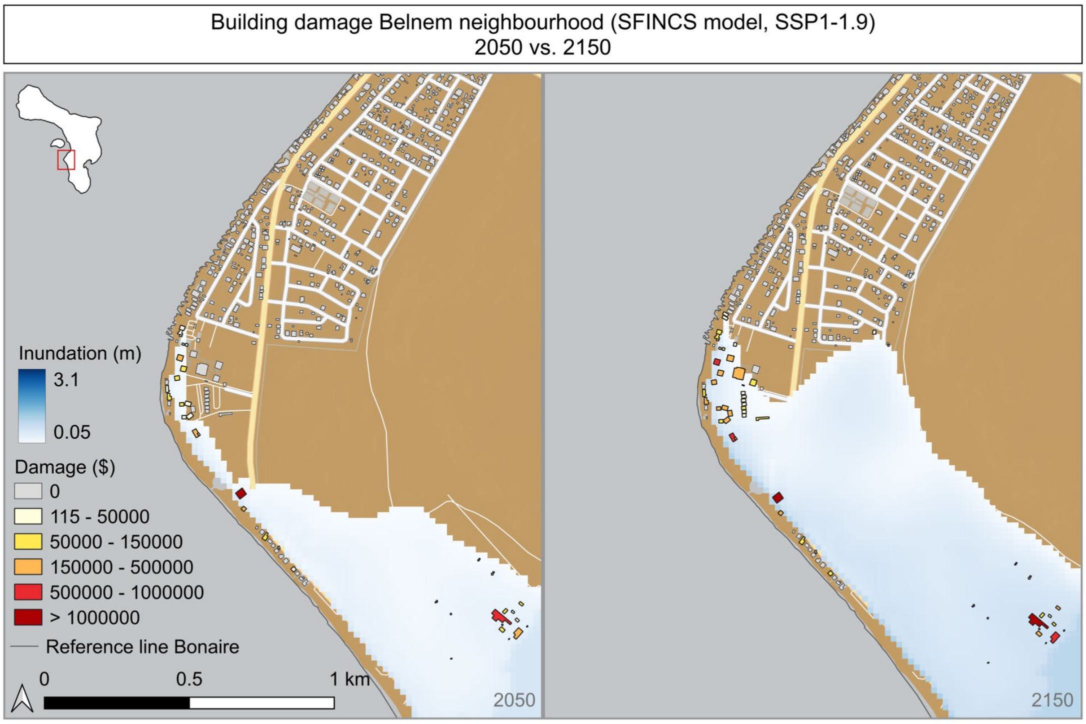


Figure 7-1 Building damage ($) in in the neighbourhood of Belnem - Climate scenario SSP1-1.9 in 2050 and 2150

Figure 7-1 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 $12.95 million. 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 $23.11 million. 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. 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 7-2 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.

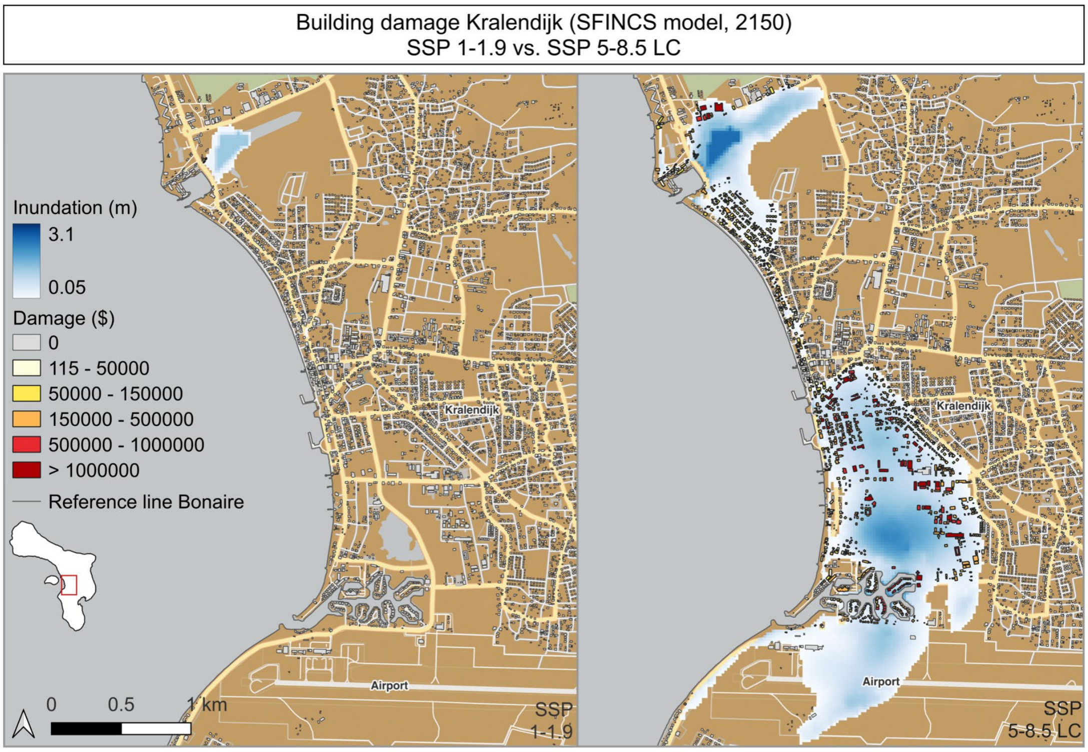


Figure 7-2 Building damage ($) in Kralendijk - climate scenarios SSP1-1.9 and SSP5-8.5 LC in 2150

7.3 Impact of storm versus permanent inundation to buildings

As described extensively in Section 6.2.2., 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 of Koks *et al*., 2022. 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 2150.

7.4 Impact of storm inundation on critical infrastructure

Figure 7-3 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. Cargill is predicted to be permanently inundated by 2050 under all climate scenarios. According to local firefighters, it can be presumed that roads are still passable until they are flooded to a depth of 40 cm, as this is the largest depth through which a first responders' vehicle can still travel. When considering the impact on infrastructure such as roadways, it has been assumed that an entire road can be considered inoperable if the maximum inundation at some point of this road is 40 cm or higher. As shown in Figure 7-3, all roads in the Southern part of Bonaire may be unusable in 2050 under both climate scenarios (SSP 1-1.9 and SSP 5-8.5 LC) due to storm inundation. Therefore, emergency services cannot reach the Cargill facilities and other buildings in these areas of Bonaire.

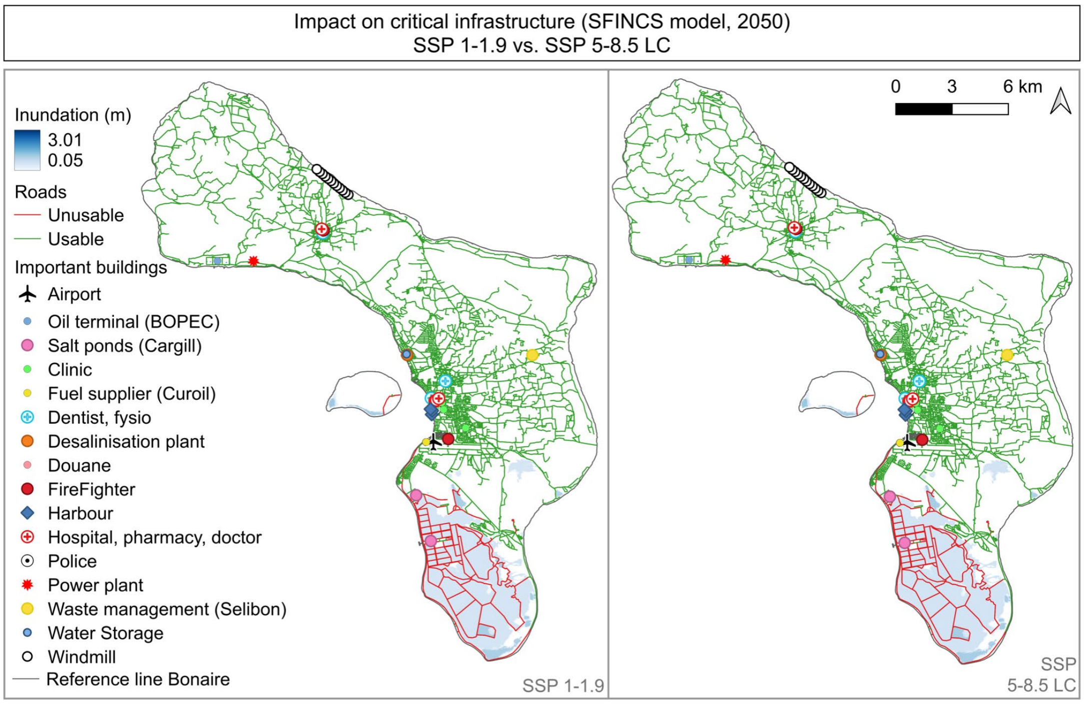


Figure 7-3 Impact on critical infrastructure on Bonaire - climate scenarios SSP1-1.9 and SSP5-8.5 LC in 2050

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 7-4 indicates that not only the infrastructure in the Southern part of Bonaire is impacted, but in climate scenario SSP 1-1.9, the road to BOPEC and the powerplant in the northern part of Bonaire is also unpassable. Furthermore, it is notable that the harbour is expected to be hit by the flood hazard in any scenario in 2150. However, the harbour 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 7-4 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.

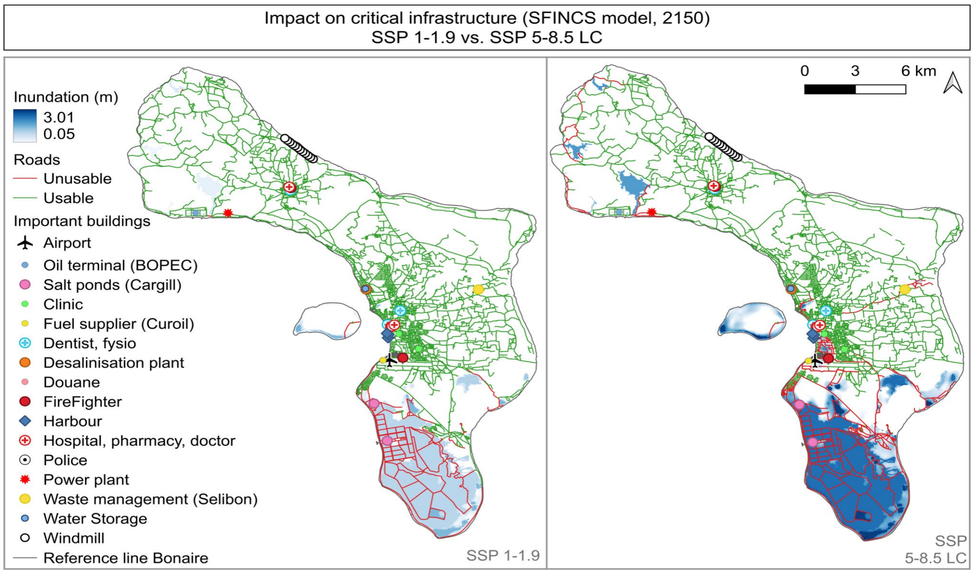


Figure 7-4 Impact on critical infrastructure on Bonaire - climate scenarios SSP1-1.9 and SSP5-8.5 LC in 2150

When zooming in on Kralendijk, it is predicted that various critical infrastructure and roads will be impacted in 2150 under climate scenario SSP5-8.5 (Figure 7-5). Almost all roads leading to the fire station and airport will be impassable, as will several roads in the city centre, including multiple roads leading to the police station. The airport, fire station, and a clinic are anticipated to be permanently flooded by 2150 under climate scenario SSP5-8.5 LC. Coastal storm flooding is also expected to cause additional damage to several other clinics and to the police station.

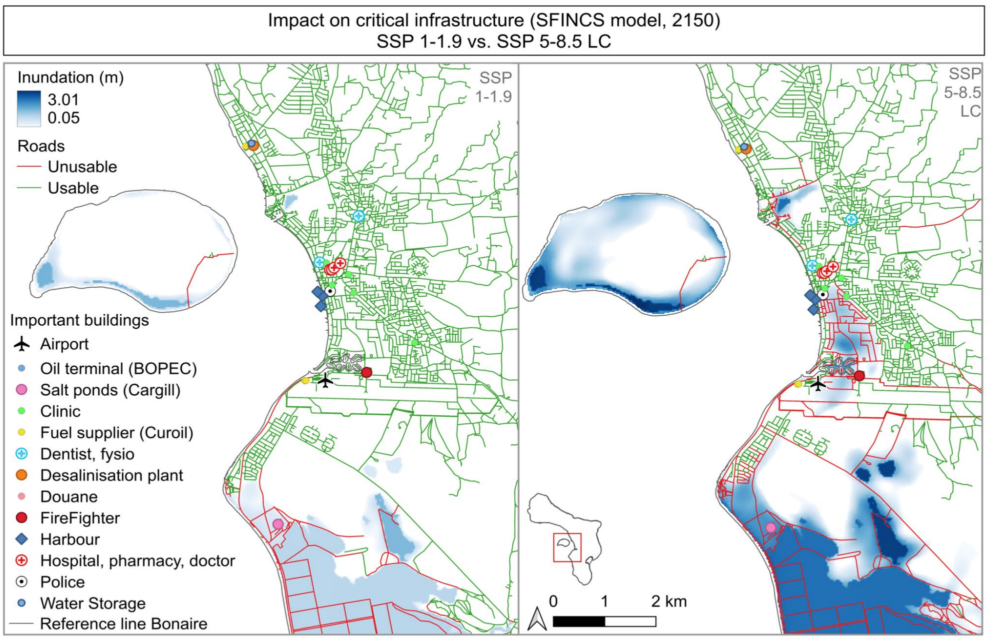


Figure 7-5 Impact on critical infrastructure on Bonaire, focus on Kralendijk - climate scenarios SSP1-1.9 and SSP5-8.5 LC in 2150

8 Impacts of ecosystem degradation on economic development

8.1 Applied methods for the analysis of impact on economic development

With visitors contributing 16.3% to its Direct GDP (CBS, 2012), and likely even more indirectly, Bonaire's economy is firmly based on tourism, particularly the mainstay activity of scuba diving (KVK Bonaire, 2020). If Bonaire is to enjoy the economic benefits of tourism in the long term, it will depend heavily on the health of the coral reefs, which are the main tourism attraction (Croes *et al*., 2019; Schep *et al*., 2013; Clegg *et al*., 2021). The demand of tourist-related industries depends on the total supply of dives that the coral reefs can facilitate. Sookram (2009) finds that reef degradation affects both the number of tourist arrivals as well as their expenditures. In this study, the concept of "social carrying capacity" is employed to predict changes in dive tourism demand. This concept captures the restricting factor of the availability of healthy reefs when visiting a diving destination (Davis & Tisdell, 1995). The social carrying capacity of the coral reef on Bonaire is calculated by multiplying the number of quality dive spots by the number of 'diveable' hours and the maximum encounters of divers per dive slot at each dive site (Koks & Van Zanten, 2015). For Bonaire, the total social carrying capacity in 2017 amounts to almost 1.5 million diveable hours.

The total annual dive demand is estimated by determining how many tourists on Bonaire are divers each year. To predict the number of stay-over and cruise divers for 2017, we adopt the levels measured in 2012, which implies that 51% of the stay-over tourists and 4% of cruise tourists engage in diving activities (TCB, 2010; Schep *et al*., 2013). Finally, based on expert opinions from local dive operators, the average demand of a diver per stay is assumed to be 10 dives (Snelder, 2022). The total dive demand for 2017 accounted for 835,867 of diveable hours. The resource balance in 2017, calculated by subtracting the total dive demand from the social carrying capacity, therefore amounted to a surplus of 629,000 dives (Figure 8-1).

To translate changes in diver demand on the tourism industry and the wider economy of Bonaire, an input-output (IO) analysis was developed for Bonaire. Such a model is used to identify and calculate the ripple effects that a change in tourism demand will have on all sectors of the local economy, not just on the tourism sector. A key strength of the analysis is that it allows for identifying both direct and indirect effects of external shocks to an economy, such as changes in tourist numbers (Rose, 2004). Based on previous IO studies for Bonaire, an IO analysis for 2017 was developed as this was the year with the most complete set of data (Kok & Van Zanten, 2015; Van de Steeg, 2009; Steenge, 2010). This IO analysis was used to link external ecological effects (i.e. coral reef degradation) to economic impacts (i.e. tourism), allowing for the estimation of economy-wide impacts of environmental shocks in Bonaire.

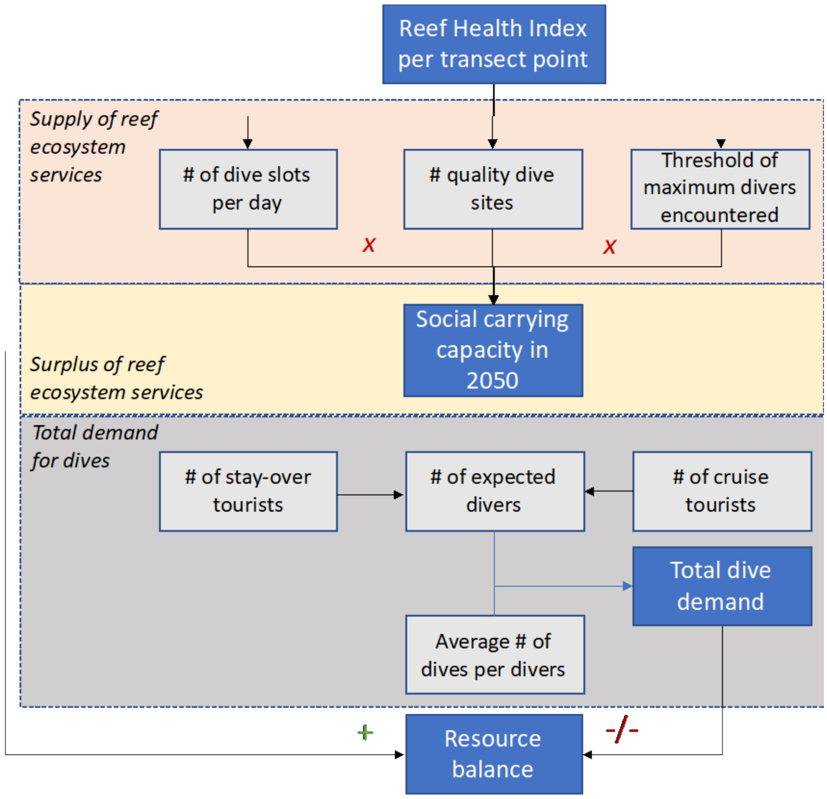


Figure 8-1 Overview of established social carrying capacity using key health indicators from Meesters (2020) extrapolated inventory of Zanke & DeFroe (2017)

The process of estimating total revenue losses was based on the number of stay-over and cruise tourist arrivals, the average numbers of nights spent on Bonaire, and the average tourist expenditures per tourist per day (Mayer & Vogt, 2016). First, assuming that divers will not visit the island if their dive demand cannot be met, the annual number of visitors to Bonaire was proxied using the resource balance (i.e. the surplus or shortage between dive supply and demand), while differentiating between stay-over tourists and cruise tourists. Second, the decline in both tourist arrivals affects the input-output table through the final tourism demand. The tourism revenue loss per tourist type is matched to the impacted industry in the IO table. Due to the multiplier effect, variances in the final demand of a specific industry will result in 'spill-over' effects to other industries. To calculate the change in the total output of each sector, a Leontief matrix was constructed. Using the Leontief multipliers, the induced changes in intermediate demand between all sectors can be determined. The resulting decrease in total output per sector can subsequently be used to assess the changes in the GDP of Bonaire, and thus to assess the impact of climate change on the economy.

8.2 Tourism demand

Climate change will have negative effects on the health of coral reefs on Bonaire, which could lead to changes in the quality of dive sites. Any changes in the quality of the dive sites is expected to decrease the supply of annual dives, thus affecting the resource balance. Resource balance depends on the supply of annual dives and the total expected number of tourist arrivals. According to a local expert (Mercera, 2022)

Bonaire aims to limit tourism arrivals to 250 thousand annually, and thus it is assumed that by 2050, ceteris paribus, 250 thousand stay-over tourists and 259.5 thousand cruise tourists will arrive on the island. A certain share of these tourists are divers. Subtracting the annual diving demand from the social carrying capacity of the coral reefs results in the resource balance of each scenario in Table 8-1. Subsequently, the surplus or deficit is calculated by dividing the resource balance by the average dive demand of an individual diver (10). The final step is calculating the split between the number of stay-over tourists and cruise tourists that cannot be facilitated.

Table 8-1 Overview of the expected diving demand and supply of quality dive sites in 2050 under each IPCC AR6 scenario. Percentages indicate change compared to baseline

Climate scenario	Baseline (2017)	SSP1-1.9	SSP2-4.5	SSP3-7.0	SSP5-8.5
Quality dive sites (#)	**89**	86 (-3%)	72 (-19%)	50 (-44%)	13 (-85%)
Average RHI score	**2.9**	3 (10%)	2 (-22%)	2 (-36%)	1 (-49%)
Social carrying capacity	**1,515,967**	1,464,867 (-3%)	1,220,722 (-19%)	848,081 (-44%)	218,455 (-86%)
Annual number of dives	**868,014**	1,394,365 (61%)	1,394,365 (61%)	1,394,365 (61%)	1,394,365 (61%)
Resource balance	**647,953**	70,501 (-89%)	- 173,643 (-127%)	- 546,284 (-184%)	- 1,117,592 (-272%)
Surplus/deficit of diver demand	**64,795**	**7,050 (-89%)**	**-17,364 (-127%)**	**-54,628 (-184%)**	**-117,592 (-272%)**
Changes in # stay-over tourist arrivals	0	0	-15,959	-50,207	-108,074
Changes in # cruise tourist arrivals	0	0	-1,406	-4,422	-9,518
Changes in final tourism demand (2017 prices)	**0**	**0**	**-$30.27 mln**	**-$95.24 mln**	**-$205.02 mln**

Scenario SSP1-1.9 .6 shows a positive resource balance, since the coral reefs are expected to have the capacity to carry all diver demand. The model predicts no decline in diver arrivals, hence, no changes in final tourism demand are expected. However, SSP2-4.5 displays a deficit of 174 thousand in the resource balance. The decline in quality dive spots decreases the social carrying capacity to a point where the dive demand exceeds the actual supply of dives. Consequently, 16.0 thousand stay-over tourists and 14.1 thousand cruise tourists are expected not to visit the island compared to the baseline scenario. This deficit progressively decreases with SSP3-7.0 and SSP5-

8.5. In SSP3-7.0, 50.2 thousand stay-over tourists and 4.4 thousand cruise tourists are expected to not travel to Bonaire. In scenario SSP5-8.5, total losses in tourism arrivals decreases to 117.6 thousand tourists, resulting from a negative balance of 108.1 thousand stay-over tourists and 9.5 thousand cruise tourists.

8.3 Input/output tables by 2050

To analyse the economic effects of changes in tourism demand on the economy IO tables were utilised and three economic scenarios were considered. Figure 8-2 presents the total output of each sector of the three economic scenarios by 2050, prior to the climate shocks of the IPCC scenarios. These structures were extracted from the underlying IO tables of 2050, assuming the “high growth,” “business-as-usual”, and “low growth” scenarios.

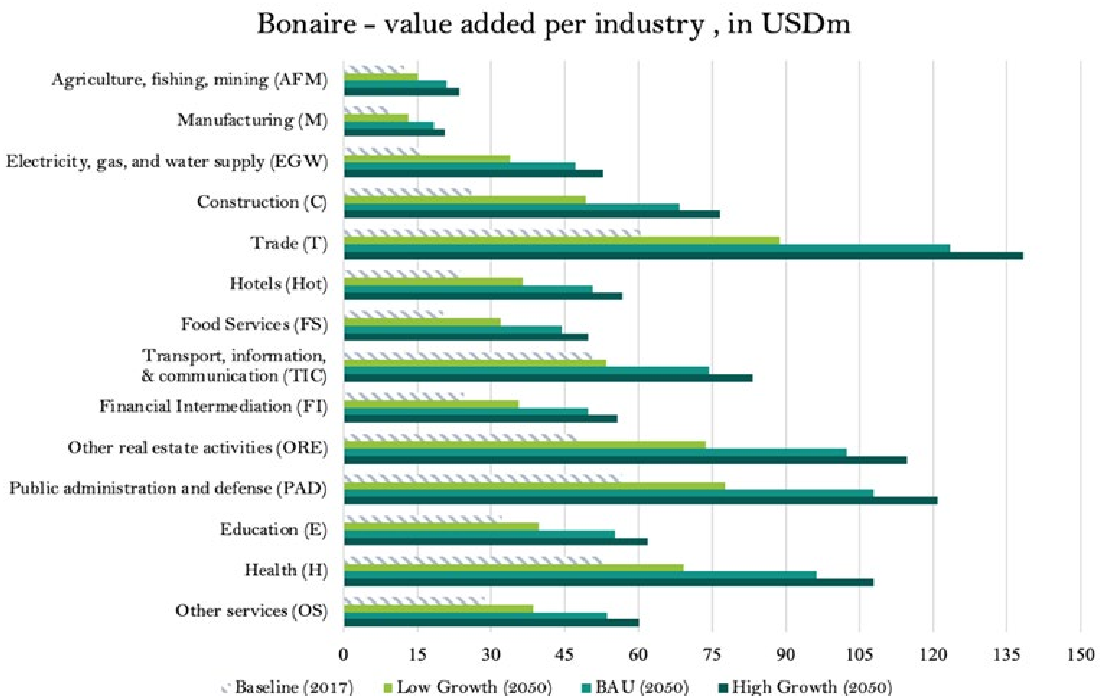


Figure 8-2 Value added per industry in Bonaire per economic scenario, in USDm

In the “high growth” scenario, Bonaire’s nominal GDP grows from 480 USDm to 1065 USDm by 2050. Based on the expected population of 27.08 thousand by 2050 (CBS, 2022). This amounts to a GDP per capita of 39,364 USD, compared to 25,000 USD in the baseline. This relatively high increase in GDP per capita would confirm that Bonaire’s strategy to make the island a premium and exclusive destination is successfully implemented since high-value immigration and tourism are being attracted. Next, the “business-as-usual” scenario returns a GDP of 951 USDm by 2050. Per capita, this equals 35.137 USD, indicating that Bonaire slowly grows to European Union averages (World Bank, 2021a). Finally, GDP grows to 684 USDm in the ‘low growth’ scenario. However, nominal GDP per capita stagnates at 25,288 USD due to population growth. Since the industries are assumed to grow with the same growth rates as the nominal GDP, the relative contribution of each industry to the total economic output of Bonaire remains the same in each scenario. Nevertheless, there were significant variances in economic output between the three scenarios. For instance, the added value of the “Trade” industry is 50 USDm higher in the “high growth” scenario than in the “low growth” scenario. Hence, the relative decline in GDP due to reef degradation will vary per scenario.

To estimate the indirect economic consequences of tourism losses, Leontief multipliers were estimated using the ‘new’ IO tables for 2050. Since it was assumed that all industries have similar growth rates within an economic scenario, the interrelations between industries did not change relative to 2017. The output multipliers range from 1.23x (Public administration and defence) to 1.82x (Hotels). The overall tourism output multiplier amounts to 1.57x, i.e., a decrease in tourism demand of 1 USDm results in a decrease in total output of 1.57 USDm. Consequently, total output in Bonaire under SSP2-4.5, SSP3-7.0, and SSP5-8.5 decreases, respectively, with 47.4 USDm, 49.2 USDm, and 321.1 USDm. In other words, less suitable dive sites leads to less tourism which subsequently results in less economic activity on Bonaire.

8.4 Indirect economic consequences

Table 8-2 summarises the total macroeconomic effects of tourism losses due to reef degradation on Bonaire. The indirect economic consequences are derived by feeding the declines in final tourism demand in each sector into the induced Leontief coefficients of the added value per sector. As determined above, scenario SSP1-1.9 does not result in any decline in tourism demand. Hence, no indirect economic consequences of reef degradation are found. In scenario SSP2-4.5, the decline of 30.3 USDm in final tourism expenditures is divided over the relevant industries according to the related expenditure categories. Subsequently, this study finds that GDP is expected to shrink with 25.7 USDm. Considering the “high growth”, “business-as-usual”, and “low growth” scenarios, Bonaire is expected to potentially experience an economic contraction of 2.4%, 2.7%, and 3.8%, respectively. Next, in scenario SSP3-7.0, the decline in the tourism expenditures of 95.2 USDm result in a GDP contraction of 80.8 USDm. In total, Bonaire’s GDP shrinks by 7.6%, 8.5%, and 11.8%, respectively, in the”high growth”, “business-as-usual”, and “low growth” scenarios. SSP5-8.5 shows the most severe indirect economic losses. Total indirect economic losses amount to 173.9 USDm, leading to a severe economic contraction of 25.4% in the “low growth scenario” case. Simultaneously, the economic damages are also significant in the “high growth” (-16.3%) and the “business-as-usual” (-18.3%) scenarios, especially when considering that the direct contribution of tourism to GDP is only 16.3% on Bonaire (CBS, 2012).

The tourism sectors such as “Hotels”, “Food services”, and “Other real estate activities” are seriously impacted in each scenario. For instance, in scenario SSP5-8.5, the added value of the “Hotels” sector shrinks by 28.7% of its initial value in 2017 (Table 8-2). The indirect consequences of tourism spending also become evident in other related industries such as the “Trade”, “Financial intermediation”, and “Other services” industries, where the latter is expected to experience a downfall in gross value added of 24.0 USDm in the worst-case scenario. All taken into account, the GDP multiplier of tourism spending amounts to 0.85x, indicating that a reduction in tourism demand of 1 USDm leads to a reduction of 0.85 USDm in Bonaire’s GDP.

Table 8-2 GDP losses under climate scenarios considering low (LG) and high (HG) GDP growth scenarios. Losses are listed per sector as loss in value added. Values are in USDM.

Sector	Baseline		SSP2-4.5			SSP3-7.0			SSP5-8.5		
	Value added LG	*Value added HG*	*Value added loss*	*% decrease under LG*	*% decrease under HG*	*Value added loss*	*% decrease under LG*	*% decrease under HG*	*Value added loss*	*% decrease under LG*	*% decrease under HG*
Agriculture, fishing, mining	**15.07**	**23.49**	0.02	*0.1%*	*0.1%*	0.53	*3.5%*	*2.3%*	0.11	*0.7%*	*0.5%*
Manufacturing	**13.16**	**20.50**	0.43	*3.3%*	*2.1%*	1.36	*10.4%*	*6.6%*	2.94	*22.3%*	*14.3%*
Electricity, gas, and water supply	**33.88**	**52.78**	1.13	*3.3%*	*2.1%*	3.55	*10.5%*	*6.7%*	7.63	*22.5%*	*14.5%*
Construction	**49.20**	**76.64**	0.32	*0.6%*	*0.4%*	1.01	*2.0%*	*1.3%*	2.16	*4.4%*	*2.8%*
Trade	**88.76**	**138.28**	3.15	*3.6%*	*2.3%*	9.92	*11.2%*	*7.2%*	21.36	*24.1%*	*15.4%*
Hotels	**36.41**	**56.72**	1.56	*4.3%*	*2.7%*	4.90	*13.5%*	*8.6%*	10.55	*29.0%*	*18.6%*
Food Services	**31.91**	**49.71**	3.27	*10.3%*	*6.6%*	10.29	*32.3%*	*20.7%*	22.15	*69.4%*	*44.6%*
Transport, information, and communication	**53.42**	**83.23**	2.91	*5.5%*	*3.5%*	9.16	*17.1%*	*11.0%*	19.73	*36.9%*	*23.7%*
Financial Intermediation	**35.72**	**55.65**	1.52	*4.3%*	*2.7%*	4.78	*13.4%*	*8.6%*	10.29	*28.8%*	*18.5%*
Other real estate activities	**73.63**	**114.71**	5.98	*8.1%*	*5.2%*	18.80	*25.5%*	*16.4%*	40.47	*55.0%*	*35.3%*
Public administration and defense	**77.55**	**120.82**	0.66	*0.8%*	*0.5%*	2.07	*2.7%*	*1.7%*	4.46	*5.8%*	*3.7%*
Education	**39.74**	**61.91**	0.17	*0.4%*	*0.3%*	0.52	*1.3%*	*0.8%*	1.13	*2.8%*	*1.8%*
Health	**69.22**	**107.83**	1.02	*1.5%*	*0.9%*	3.20	*4.6%*	*3.0%*	6.89	*10.0%*	*6.4%*
Other services	**38.57**	**60.10**	3.54	*9.2%*	*5.9%*	11.20	*29.0%*	*18.6%*	23.98	*62.2%*	*39.9%*
Total	**656.2**	**1,022.4**	25.7	*3.9%*	*2.5%*	81.3	*12.4%*	*8.0%*	173.9	*26.5%*	*17.0%*

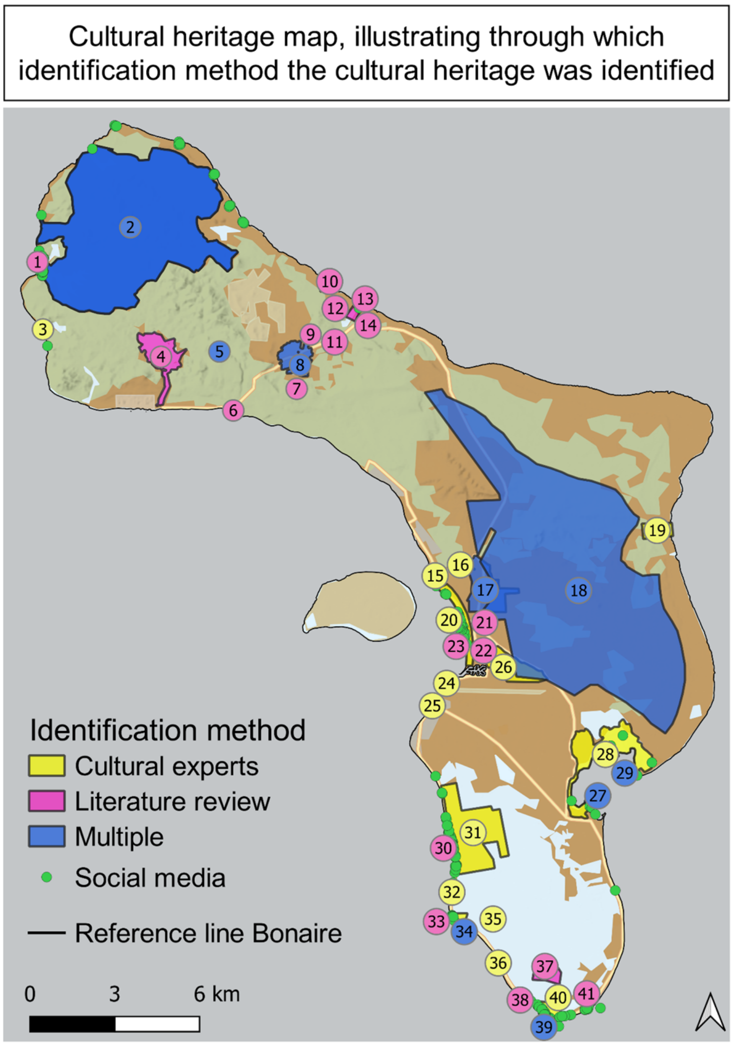
9 Impacts on cultural heritage

9.1 Applied methods to analyse impact on cultural heritage

In order to identify the tangible cultural heritage (TCH) and intangible cultural heritage (ICH), a variety of research methods is applied. First, The TCH and ICH on Bonaire were identified by literature review, including (I) the beleidsnota Cultuur, (II) the *Intangible Cultural Heritage Bonaire*'s website, and (III) various academic articles. Second, the desk research was complemented with interviews with five experts from culturally engaged non-governmental organisations (NGOs) and foundations on Bonaire, such as *FuHiKuBo* and *Hòfi Kultural Bonaire*. Third, participatory mapping (PM) was used to further identify and validate Bonaire's cultural heritage. Respondents were shown a map of Bonaire and asked to pinpoint the TCH and ICH they value and find important for the Bonairian culture, which was later digitised into polygons on a map using QGIS. The mapping was not only performed with cultural experts, but also with Bonairian residents (living at least 2,5 years in Bonaire). Finally, social media analysis was employed to validate the findings of the literature review, PM, and expert interviews. 1137 Pictures posted by tourists and residents on the platform Flickr we used (Wolfs Company, *forthcoming*). The effects of climate change on the identified ICH are based on expert interviews and those on TCH by means of the determined coastal inundation hazards.

9.2 Tangible cultural heritage

Figure 9-1 combines the cultural heritage identified during the literature with the heritage identified during the fieldwork and social media analysis. Some locations have been identified in all three analyses, however, there are also differences in the outcomes of the three methods. The literature review identified multiple locations around Rincon (e.g. 10, 12, 13, & 14 on the map) and traditional buildings in Kralendijk (e.g. 21, 22, & 23) which were not mentioned during the fieldwork. The fieldwork revealed locations that are important for fishing (19 & 20) and for recreation (24 & 25). The social media analysis features cultural heritage around Washington Slagbaai and mostly Boka Slagbaai, Kralendijk, the salt pans, the slave huts, Willemstoren, and Lac Bay, thereby validating the literature review and fieldwork results. Photographs of the identified TCH can be found in Appendix C.



1	Boka Slagbaai
2	Washinton Slagbaai
3	Playa Frans
4	Gotomeer
5	Dos Pos
6	Landhuis Karpata
7	Lourdes grotto
8	Rincon
9	San Ludovico catholic church
10	Piedra di Boneiru
11	Mangazina di Rei
12	Kaomati
13	Boka Onima
14	Indian inscriptions
15	Playa Lechi and tamarind tree
16	Hòfi Kultural
17	Antriol
18	Kunuku area
19	Lagun
20	Playa
21	Pasa Machi Mimi
22	Bestuurskantoor
23	Fort Oranje
24	Donkey Beach
25	Bachelor's Beach
26	Tera Kòrá
27	Sorobon
28	Mangroves
29	Lac Cai
30	Blue obelisk
31	New salt pans
32	Pink Beach
33	White obelisk
34	White slave huts
35	Old salt pans
36	Atlantis fishermen's hut
37	Flamingo Sanctuary
38	Red obelisk
39	Red slave huts
40	Old salt pans
41	Willemstoren

Figure 9-1 Map comparing the cultural heritage identified during the literature review, by the cultural experts and Bonairian residents, and social media analysis

The majority of Bonaire's TCH is located in coastal, mostly low-lying areas, and is vulnerable to permanent inundation and additional flooding from storm surges. The vulnerability of identified TCH to permanent and storm flooding was examined. As shown in Figure 9-2, in 2050 no identified TCH in the North will be vulnerable to permanent or storm flooding, but all TCH in the South is considered susceptible already under climate scenario SSP1-1.9.

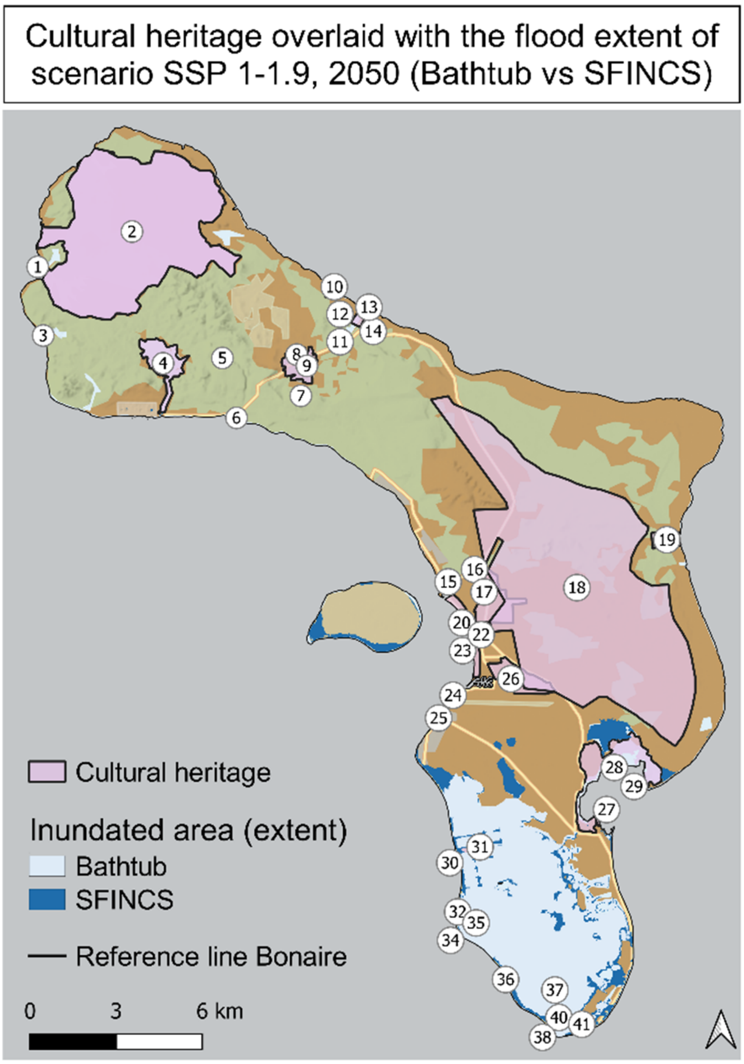


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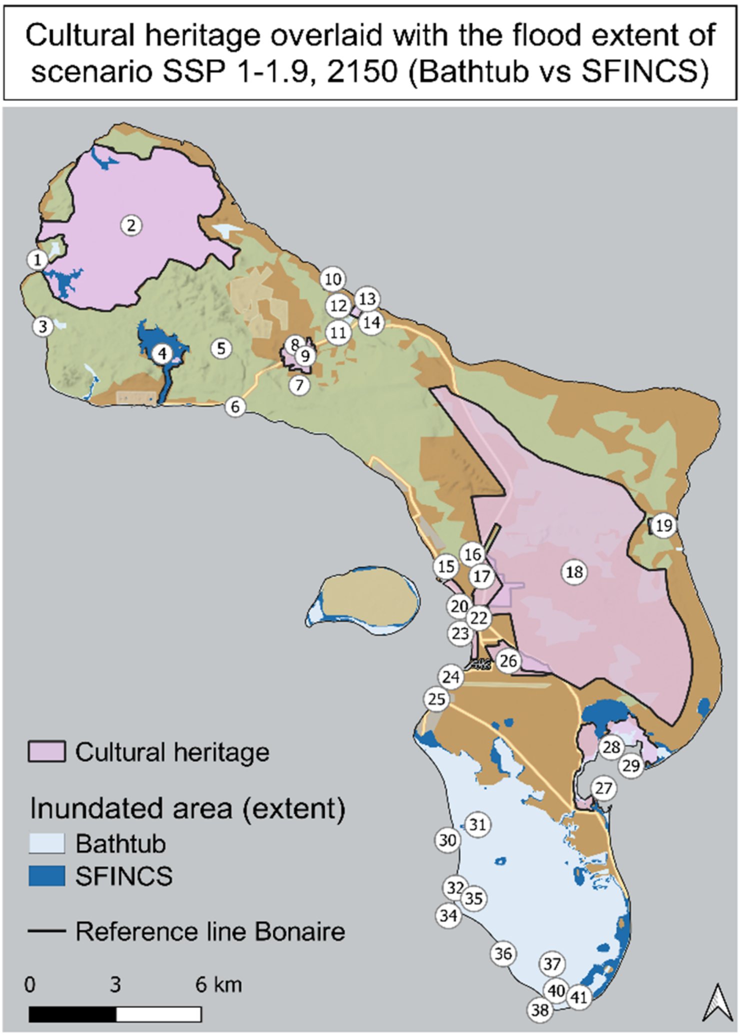
Figure 9-2 Cultural heritage identified on Bonaire overlaid with the inundation map for the SSP 1-1.9 scenario in 2050

Permanent and coastal storm inundation for climate scenarios SSP 1-1.9 and SSP5-8.5 LC in 2150 are analysed and visualised in Figure 9-3 and 9-6. The maps present the identified TCH on Bonaire and indicate with colour coding whether the TCH is (I) not projected to be at risk (green), (II) at risk of storm inundation (orange), or (III) at risk of permanent inundation (red). Due to varying data accuracy, for instance in the coastal elevation model (DEM), and the uncertainties inherent in climate change, the inundation maps are an indication of what could happen in the different scenarios, but also come with a certain level of uncertainty.

Figure 9-3 shows that in 2150 under the SSP1-1.9 scenario, permanent inundation is predicted to impact Boka Slagbaai and Playa Frans in the Northern part of Bonaire. In Bonaire's most Southern part, everything besides the red obelisk is projected to be permanently inundated. The red obelisk is at risk from storm inundation. Hence, permanent inundation poses a significant threat to the TCH at Boka Slagbaai, presented in figure 9-4, and the TCH in the South, such as the salt pans, the slave huts seen in figure 9-5, fishermen's huts, obelisks, and Willemstoren, among others.



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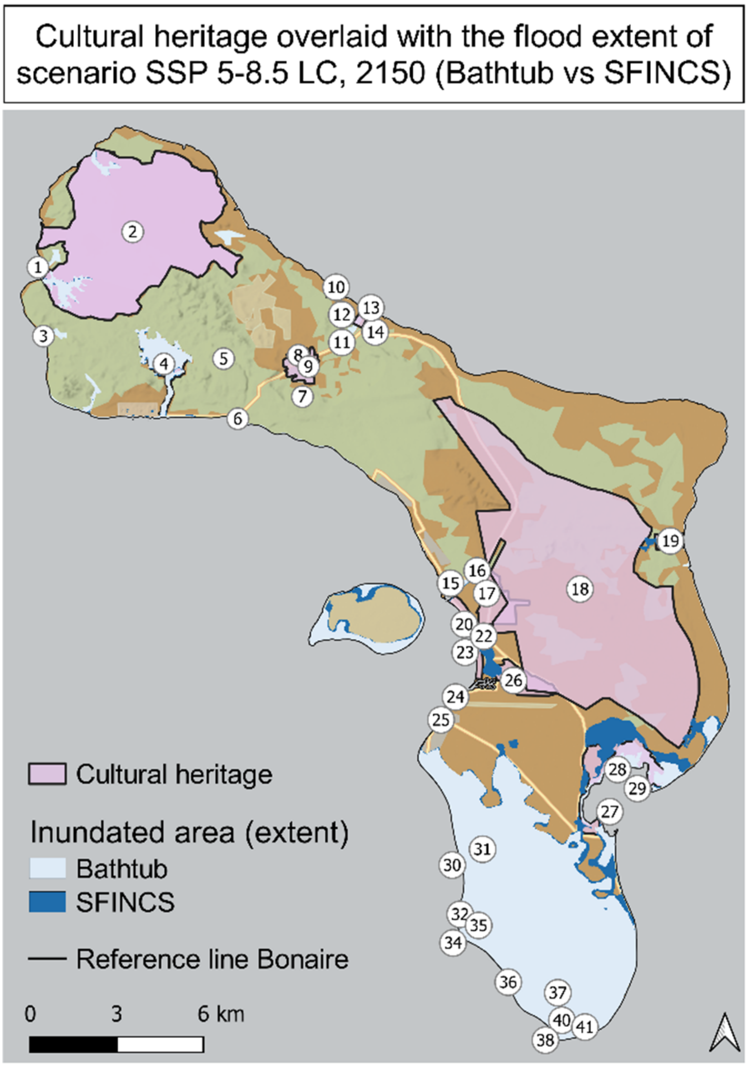
40	Old salt pans
41	Willemstoren

Figure 9-3 Cultural heritage identified on Bonaire overlaid with the inundation map for the SSP 1-1.9 scenario in 2150

Figure 9-4 The house at Boca Slagbaai with a protective seawall (Buijs, 2022)

Figure 9-5 The white slave huts (Buijs, 2022)

Compared to SSP1-1.9, the SSP2-4.5 SSP5-8.5 scenarios for 2150 show similar patterns in terms of the TCH that is predicted to be inundated. The three scenarios in 2150 show minor inundation differences and do not suggest additional affected TCH. However, the SSP5-8.5 LC scenario for 2150 in figure 9-6 shows a more significant increase in inundation. The inundation in this scenario affects a larger part of Bonaire’s Eastern coast and a major part of Klein Bonaire. Due to SLR under climate scenario SSP5-8.5 LC, relatively small parts of the Washington Slagbaai and Gotomeer in the Northern part are projected to be permanently inundated, as is the Red Obelisk in the South. Additionally, TCH at the eastern coast is at risk from coastal storm inundation, including Fort Oranje and Playa (the centre of Kralendijk), as well as a small part of the kunuku area. Thus, inundation due to SLR could trigger forced moving in the long run, which can negatively affect culture if people have to move away from their long-term homes or traditional neighbourhoods.



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38	Red obelisk
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40	Old salt pans
41	Willemstoren

Figure 9-6 Cultural heritage identified on Bonaire overlaid with the inundation map for the SSP 5-8.5 Low Confidence scenario in 2150

In 2300, under the SSP1-2.6 LC climate scenario, Boka Slagbaai, Playa Frans, Washington Slagbaai Gotomeer in the north and everything south of the mangroves are projected to be permanently inundated. Under the climate scenario SSP5-8.5 LC, all identified TCH, with the exception of those in the North-Western region (5-12 & 14), are anticipated to be permanently flooded as a result of SLR (Appendix D).

9.3 Intangible cultural heritage

Climate change can also threaten ICH and traditional ways of life in Caribbean SIDS due to extreme weather events and rising temperatures (UNESCO, 2021). This section elaborates on identified and selected ICH on Bonaire, including fishing, agriculture, and festivities. It is not possible to distinguish between the varying effects of climate change on ICH on the basis of different climate projections. Therefore, no distinction between scenarios and time scales has been made; rather, an overview of potential consequences on ICH has been provided.

9.3.1 Fisheries

Fishing is an iconic and important part of Bonairian culture and indigenous people (Caquetio, a strain of the Arawak people) relied on fisheries and contributed the first cultural elements. As such, fishing is one of the oldest economic activities that is still performed in the Dutch Caribbean (CE5; Dutch Caribbean Nature Alliance, 2019; Mac Donald, 2018; PM6). This is demonstrated by the fact that the circle on the Bonairian flag represents a compass, alluding to the Bonairians' reputation as skilled sailors and fishermen (CE4). Until 50 years ago, most of the island’s population relied mainly on fish for their protein intake (Dutch Caribbean Nature Alliance, 2019). An important part for the fishery practice are the fishermens’ huts, such as those found in Sorobon and on Atlantis beach, where the fishermen can stay overnight before leaving for an early fishing trip (CE1).

Bonaire’s traditional fishing culture is at risk of climate change impacts. Healthy reefs and mangroves are essential for the Bonairian fishing practices (CE1). However, climate change negatively affects both, as increasing ocean temperatures, ocean acidification, and stronger storms resulting from climate change seriously threaten coral reef health and weaken the reefs’ resistance to diseases (Dutch Caribbean Nature Alliance, 2019; Hoey *et al*., 2016; Verweij *et al*., 2020). As a result, the reef fish habitat is destroyed, reducing Bonaire’s fishing possibilities (CE5; Hoey *et al*., 2016). Since professional fishermen, as opposed to traditional fishermen, do not fish near coral reefs, but instead target pelagic fish species, coral reef degradation may not have a direct effect on the productivity of fisheries, but rather on recreational fishing (CE4).

Rainwater from heavier precipitation, and soil erosion from periods with decreased precipitation, carry sediment to the ocean and negatively affect the reefs and marine life (Goatley & Bellwood, 2013; HE5; Verweij *et al*., 2020). Accordingly, declining reef health due to climate change, along with marine pollution and human factors, are certain to have a negative impact on Bonairian fishing through their threat to important fish stocks (Dutch Caribbean Nature Alliance, 2019).

9.3.2 Agriculture

Agriculture is embedded in Bonairian culture. In the past, everyone grew their own food, and most of the inhabitants were self-sufficient through growing crops and keeping goats (CE4; Verweij *et al*., 2020). Bonaire is currently 99% dependent on imported food (Verweij *et al*., 2020). In the past few years, the island governments and inhabitants have started initiatives to take up food growth practices again (CE4; Lotz *et al*., 2020). CE4 suggests two possible reasons for this result: (i) the government and NGOs are actively promoting agriculture, and (ii) the border closure with Venezuela in 2018 led to a decrease in availability of fresh fruits and vegetables. The reliance on imported food may influence the prices (Wageningen University & Research, 2021), although self-cultivated food is not necessarily less expensive than imported food. Despite the government's initiatives, food production on the islands of Bonaire remains limited, and the majority of food is imported from neighbouring nations (Lotz *et al*., 2020).

Climate-related impacts on the Bonairian agriculture due to hurricanes, storms, and droughts would damage the island's cultural identity (CE1). On the one hand, CE4 argues that climate change currently causes little concern for the Bonairian agriculture sector, as the sector is not properly developed yet. On the other hand, changing weather, such as drier seasons or heavier rain (CE1; PM2; PM4), already directly affects the small number of current farmers and their practices (CE1). Bonairian farmers state that there has been less rain on Bonaire (Natural disasters Bonaire, n.d.). Such agricultural droughts are a threat to food production, as they lead to crop damage and consequently smaller yields (IPCC, 2022).

Many Bonairians have a piece of land (owned or rented) with a simple house (Public Body Bonaire 2010a). These small rural parcels are known as kunuku's, and while a portion of them are still used for agriculture and recreation, the majority have been abandoned. The kunuku's provide a variety of services and environmental, economic, and cultural values to the Bonairians (Lotz *et al*., 2020). Water wells such as the Dos Pos are essential for the kunukeros (CE1), but these groundwater systems may also be impacted due to climate change induced salinization, which can disturb the freshwater supplies (PAHO, 2019). This may pose a problem for traditional Bonairian agriculture as it impacts agricultural yields (Verweij *et al*., 2020) and threatens the provision of ecosystem services associated with the kunuku's.

9.3.3 Festivities

It is not exactly known how the many festivities on Bonaire might be affected by climate change. Respondents have put forward that they think none will be affected, as only a direct natural disaster (e.g. an earthquake), can stop the Bonairians from celebrating Dia de Rincon and other festivities (CE2). Although they could adapt to the heat by celebrating later during the day or in the evenings (CE3), a tradition and, hence, the culture of Bonairians will be impacted. One festival that could be specifically impacted by climate change is Simadan: the harvest festival (CE1). During this festival, which CE3 already sees happening less, the farming communities used to go to different farmers to help out with planting the crops, cutting the grains, and then dance, sing, and eat together (CE1). However, if getting a harvest becomes more difficult, Simadan may not take place anymore (Beleidsnota cultuur, 2010; CE1).

10 Impacts on human health

10.1 Applied methods to analyse impact on public health

The effects of climate change on various aspects of Bonairians' health conditions are determined by focussing on the impacts on vector-borne diseases, non-communicable diseases, and mental health, among others. In order to explore the current health situation on Bonaire and the possible impacts on public health associated with climate change, desk research is combined with expert interviews. The literature review included sources from the RIVM (2017), OLB (2020), WHO (2018a; 2018b; 2020; 2022), PAHO (2020) and the World Bank (2021) among others.

Since there is limited knowledge on the climate change effects on health on Bonaire, interviews with health experts were necessary to explore how climate change is predicted to affect public health on Bonaire. The interviews also served to determine whether Bonaire already sees climate change impacts on public health and how the island has coped with past extreme events. The interviewed experts have knowledge of health (e.g. infectious diseases) and the Caribbean (e.g. from the Caribbean Public Health Agency, CARPHA, and PAHO), but also experts with specific health knowledge to Bonaire participated in 40-60 minute semi-structured interviews. In total, seven health experts participated in the research.

It must be noted that this study did not attempt to quantify the climate change impacts on health. This decision has been taken in response to a statement by PAHO, that "because of the complexity of the processes involved, it is difficult to estimate the magnitude of the possible effects of climate change on health" (PAHO, 2017, p.13). Similarly, an interviewee (health expert 2) put forward that the impact of climate change on health is 'only' "measurable from the fact that we see an increase in illnesses". Moreover, this part of the study does not take different climate scenarios into account. Despite the belief that there will be additional effects on health when temperatures increase further and that the effects of climate change become more visible, health experts emphasise that the differences between the scenarios are highly uncertain, and argue in favour of focusing on the general effects of climate change on health (Health expert 7, 2022).

10.2 Impacts of climate change on public health

Although climate change induced floods can result in increased injury and accidental mortality (WHO, 2021), such physical trauma only makes up a minor part of the health climate change impacts. In reality, many more impacts can be seen in terms of vector-borne diseases, non-communicable diseases, mental health, and other health problems (PAHO, 2020). Akpinar-Elci and Sealy (2014), for example, point out that climate change impacts can worsen diseases that small, tropical islands like Bonaire are vulnerable to, such as heat stress, asthma, and vector-, food-, and water-borne diseases.

10.2.1 Vector-borne diseases

Vector-borne diseases are infectious diseases caused by parasites, bacteria, or viruses, and are spread by vectors, such as mosquitoes or ticks (WHO, 2020). Bonaire hosts the viral mosquito-borne diseases chikungunya, dengue, and zika (WHO, 2020). Chikungunya causes fever and severe joint pain that can become chronic (PAHO/WHO, n.d.). Dengue is mild and asymptomatic in 80% of the cases, however it can result in flu-like illnesses and develop into severe dengue (WHO, 2022). Zika includes symptoms like fever, conjunctivitis, muscle, and joint pain (WHO, 2018a). A zika infection during pregnancy can lead to congenital malformations in born infants and neurological complications (WHO, 2018a). So far, there are no cures for these vector-borne diseases and chikungunya and dengue can cause death in case of late detection and improper access to medical care (PAHO/WHO, n.d.; WHO, 2018a; WHO, 2022). In 2016, Bonaire reported 37 cases of chikungunya and 45 cases of dengue (Duijster & Hahné, 2016).

Climate change is likely to influence vector-borne diseases as it creates a more suitable climate for vector survival (PAHO, 2020; WHO, 2022). Changing climate conditions in countries with endemic dengue have facilitated dengue transmission by almost 10% since 1950 and climate change is expected to increase dengue transmission by significantly (Sealy, 2018).

A warmer climate, along with increased humidity, speeds up mosquito reproduction and disease transmission risk of dengue for example (PAHO, 2020; Rocklöv & Tozan, 2019). The hotter the climate, the faster the mosquitoes breed, the shorter the diseases' incubation time, and the higher the risk of disease transmission (Akpinar-Elci & Sealy, 2014; HE1; Sealy, 2018; WHO, 2017b). Models predict this to happen with dengue transmission in many tropical regions as temperatures will increase (Åström *et al*., 2012; Iwamura *et al*., 2020). The climate change induced temperature changes could also result in a suitable minimum temperature for malaria transmission in the Caribbean, a region where malaria is not endemic (Nurse *et al*., 2014).

The increased incidence of extreme weather events, such as storms leading to pluvial and coastal flooding, could further increase the exposure of Caribbean SIDS populations to vector-borne diseases (CDC, n.d.). Flooding can "facilitate the stagnation of water, which leads to an increase in breeding sites" (PAHO, 2020, p.54) and temporarily increases mosquito numbers two to three weeks after (HE7) and increases the number of vector-borne diseases (HE1). However, some extreme events, such as heavy precipitation, can destroy the mosquitoes' breeding sites (PAHO, 2020).

Changes in vector-borne disease incidence in the Caribbean are already seen. HE1 specifies that the mosquito breeding process has already shortened from ten to twelve days to five to seven days. HE2 puts forward that, with the outbreak cycles decreasing from about ten years in the past, vector-borne diseases seem to have accelerated to a year or two now (HE2). Lastly, it has been argued that climate change may have played a role in the emergence of chikungunya in a variety of Latin American and Caribbean countries (Yactayo *et al*., 2016).

10.2.2 Non communicable diseases

It is expected that climate change will directly impact non-communicable diseases through increasing temperatures, extreme weather events, and air pollution (PAHO, n.d.b, HE1; HE7). Respiratory, cardiovascular, circulatory, and kidney problems are among the ailments that could be exacerbated (PAHO, n.d.b). Increasing temperatures will aggravate non-communicable diseases by worsening the symptoms felt from these diseases (HE7; HE1; Public Health Department Saba, n.d.). In line with this, PAHO (2020) has determined an increase in cardiovascular diseases as a result of the thermal stress incurred during heat waves, and Liu and colleagues (2015) have found a correlation between heat and cardiovascular disease deaths.

Extreme weather can also cause patients with non-communicable diseases to experience a worsening of their symptoms because “their care may be jeopardised” (HE7). HE3 adds that patients suffering from non-communicable diseases often live in houses that are vulnerable to flooding, which may result in a negative impact on the patients’ access to healthcare during heavy precipitation events. It could be that in such instances the patients lose their housing, do not use their medication in the right way, or get misaligned with their sugar levels (HE3). As such, the climate change impacts on the patients’ health will be exacerbated by their social status. As many Caribbean countries, including Bonaire, already suffer from high incidences of NCDs (HE2; HE4), higher incidences and hospital admissions due to non-communicable diseases are likely to worsen their situation and put even more burden from non-communicable diseases on the hospital services (HE2).

Additionally, climate change’s impact on air quality might exacerbate the impact air pollution already has on human health in the Caribbean (Macpherson & Akpinar-Elci, 2015). More specifically, climate change will change the concentration of respiratory allergens in the air (D'Amato *et al*., 2014). This is partly due to high temperatures (PAHO, 2020) and extreme weather events, such as heavy precipitation and flooding, that foster mould, fungi, and other bioaerosols (Ivey *et al*., 2003). Consequences of this can be an increase in allergic rhinitis, asthma, and respiratory problems (HE3; PAHO, 2020; WHO, 2009). HE3 emphasises that this is especially problematic for people who already have health problems in the form of non-communicable diseases, which are widespread on Bonaire. In line with this, research has already touched upon increased mortality and morbidity due to respiratory problems related to heat (Patz *et al*., 2014).

Changes in non-communicable diseases in the Caribbean can already be seen. HE2 puts forward that CARPHA is seeing a higher incidence of non-communicable diseases because they are affected by climate change. HE1 confirms that differences are being seen on the chronic disease side and that this has an effect on the whole Caribbean.

10.2.3 Heat-related stress

An increase in temperature caused by climate change makes Bonairians more susceptible to heat-stress disorders. Although specific data on changes in daytime and nighttime temperatures for Bonaire are unavailable, projections indicate an upward trend for both warm days and nights in the Caribbean as a whole. Cool days, on the other hand, are predicted to decrease. The predicted range of very warm days and nights for the Caribbean region is broad. For example, predictions range between 51 and 251 warm days and 24 and 360 warm nights by the end of the century for RCP 8.5 (The Caribbean Development Bank, 2020).

There are definite and absolute limits to how much heat exposure an individual can tolerate. More frequent and intense heat waves can have a direct effect on health through an expected increase in heat-related illnesses, such as the most commonly found heat-related exhaustion and heat stress, but also heat strokes and heat-related mortality (HE1; Health Canada, 2011; PAHO, n.d.b; WHO, 2021). Death rates have been shown to increase during heat waves and deaths due to heat mostly come from heat stroke, but can also be related to cardiovascular diseases (Akpinar-Elci & Sealy, 2014; CDC, 2020; Sealy, 2018). Vulnerable populations, such as the elderly and people with severe obesity, as well as people with underlying conditions are especially susceptible to disorders and mortality from heatwaves. This is relevant for Bonaire, whose proportion of obese inhabitants (more than 30%) is relatively high compared to Northern Europe (RIVM, 2017; Openbaar Lichaam Bonaire, 2020). In addition, from 2019 to 2030, the percentage of individuals older than 65 years is projected to increase from 13% to 19% (CBS, 2019), and hence increasing the vulnerability of the Bonarian population to heat-related disorders and mortality. Kovats and Hajat (2007) explain that “risk factors can also be categorised as intrinsic (age, disability) and extrinsic (housing, behaviours); the latter vary according to location and adaptations to the local climate.” The extrinsic risk factors suggest that differences in vulnerability exist between people from different social classes, since not all people may have the means to adapt their housing conditions to protect themselves from heat exposure.

Heat-related stress can also occur as a result of an extreme weather event, i.e. hurricane, when people lose access to fans and air conditioning (CDC, n.d.). HE7 assumes that with a faster increase in temperatures heat stress may be exacerbated more. Poorer people on Bonaire may be disproportionately hit by heat-related stress for their bodies, as they do not have the financial means to keep their homes at bearable temperatures (HE3).

HE5 adds that higher temperatures prevent people from moving as they prefer to stay inside (HE7), and that the current Bonairian hot climate from July to October are likely to already have negative impacts on health, although it has never been quantified (HE4).

10.2.4 Malnutrition and food insecurity

Climate change is expected to affect undernutrition on Bonaire, which is a deficiency of nutrients, and food insecurity. Climate change can lead to indirect impacts through socio-economic systems in the form of undernutrition and food security problems (PAHO, n.d.b; WHO, 2021). Bonaire is currently 99% dependent on imported food (Verweij *et al*., 2020). HE4 confirms that Bonaire does not produce its own fruits and vegetables, and that Bonairians only keep a small number of goats and chicken for consumption. Climate change with its consequent changes in temperature, drought events, ocean warming, and ocean acidification is likely to cause a reduction in crop, livestock, or fisheries yield, thereby posing strong risks to food availability and causing further increases in the cost of healthy food (IPCC, 2022). As a result, undernutrition could occur. Furthermore, rising temperatures and limited budgets already lead to trade-offs having to be made between, for example, spending money on nutritious food for healthy nutrition intake and electricity for air conditioning to protect against heat-related disorders. (HE3). Rising prices and temperature changes could exacerbate these trade-offs, indicating that the socioeconomic status of Bonairian residents could impact their susceptibility to the health effects of climate change. PAHO (n.d.b) finds that there could even be combined effects from the increased incidence of infectious diseases and undernutrition. Additionally, undernutrition can have an even more extreme effect on children, through the chronic effects of stunting and wasting (PAHO, n.d.b).

Extreme weather events are not necessarily seen as a threat to food security on Bonaire, because the Netherlands will assure emergency supplies, as was provided by the Royal Netherlands Navy for St. Maarten after hurricane Irma (CE4). HE4 also agrees that events like pandemics will likely not lead to food insecurity on Bonaire. During COVID-19, the shipping industry was seen as essential and did not experience any troubles (World Bank, 2021). However, the World Bank (2021) has found that COVID-19 affected food prices on Bonaire, which could result in unhealthier eating and associated health consequences.

10.2.5 Water-borne diseases

Food- and water-borne diseases result from the consumption of food or water that is contaminated through environmental pollution or unsafe food storage or processing (WHO, n.d.). The government's 2020 health report does not report on food- and water-borne diseases on Bonaire, but literature considers diarrheal diseases and leptospirosis relevant food- and water-borne diseases in tropical climates (PAHO, 2019; Sealy, 2018).

Climate change can have an indirect effect on water-borne diseases and other water-related health impacts mostly due to increased exposure of the population to pathogens (WHO, 2021; PAHO, n.d.b). Heavy rainfall on Bonaire sometimes leads to high water standing in the neighbourhoods. As such, heavy rainfall and floods can pollute drinking water with pathogens, fostering water-borne diseases such as diarrheal diseases, gastroenteritis, and leptospirosis (HE7; PAHO, 2020; Sealy, 2018; WHO, 2017b).

Climate change can also have a negative impact on skin diseases. Due to heat-related humidity, the skin can be damaged and become infected (PAHO, 2020). Even though it is not known whether this is related to climate change, the WHO (2019) has found 549 new cases of skin melanoma in the Caribbean in 2018.

10.2.6 Mental health

Climate change is expected to affect mental health on Bonaire. People with existing mental health problems are part of one of the groups within society that are most vulnerable to the negative consequences of climate change (Patz *et al*., 2014; PAHO, 2020). Additionally, climate change can lead to newly developing mental illness and stress in multiple ways (HE4; PAHO, n.d.b; WHO, 2021). The impact of climate change on mental health is important, as the mental health consequences can affect individuals, or even whole families, for months to years (The Climate Institute, 2011).

Extreme weather events that are related to climate change, such as floods, drought, and hurricanes can lead to mental health issues appearing before, during, or after their occurrence (PAHO, 2020). HE1 also puts forward that impacts on mental health can be seen in the aftermath of extreme weather events such as storms and hurricanes, as these come with psychological trauma for the survivors who may have had to leave their homes and had to live in shelters (CDC, n.d.; HE4). Research shows that more than half of adults suffer from depression after natural disasters and that 30 to 40% of extreme weather event survivors, especially from flooding (Alderman *et al*., 2012), suffer from post-traumatic stress (Akpinar-Elci & Sealy, 2014; Goldmann & Galea, 2014; Sealy, 2018). Moreover, heat waves can lead to an increased number of hospital admissions due to mental health problems (Khalaj *et al*., 2010), mostly because people with mental health issues find it difficult to adapt to very high temperatures (Vida *et al*., 2012). Other psychosocial problems that can result from extreme weather events are alcoholism and drug abuse (Silove *et al*., 2006). Furthermore, during extreme weather events or pandemics, the burden of psychosocial problems in the population may increase, for example, as a result of lost employment and/or (property) damages (PAHO, 2020).

Climate change potentially increases the risk of pandemics (FAO, 2005), which also drastically affect physical and mental health. With COVID-19, the number of mental health patients on Bonaire has increased from 159 clients in 2019 to 286 clients in 2020 (World Bank, 2021). Extreme weather events and pandemics can also impact the mental health of health professionals and reduce their ability to deliver adequate healthcare (HE7). Accordingly, HE7 emphasises the importance of mental health training for health professionals. Moreover, participatory mapping shows that Bonairian residents strongly value nature and link it to their cultural identity. As a result, when the ocean and its coral reefs are degraded through climate change, their positive contribution to public mental health on Bonaire will be greatly diminished (World Bank, 2020).

Figure 10-1 shows a simplified flowchart of how climate change is expected to affect public health on Bonaire, which is based on information from expert interviews and literature review. However, impacts on health are complex and cannot directly be quantified.

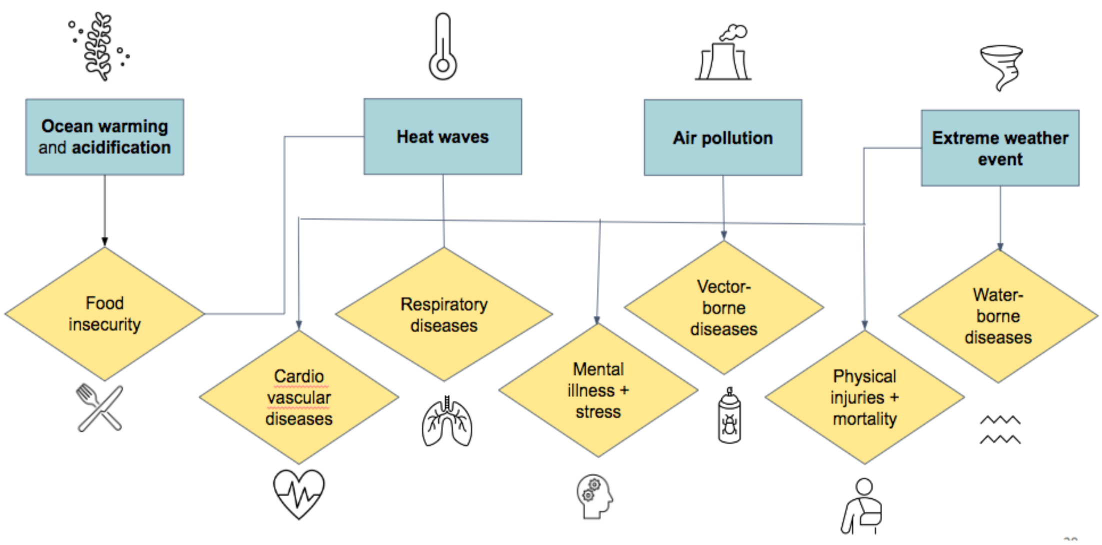

Figure 10-1 Flowchart showing the simplified impact of climate change on Bonairians' public health

11 Adaptation measures

As a result of the diversity of climate change's impacts, climate adaptation measures can encompass a vast array of options that provide protection against the consequences. This study will therefore concentrate on adaptation measures for three of the most obvious effects of climate change, including heat, drought and flood risks. Whereas adaptation measures for the prior two challenges are qualitatively described in section 11.3, a participatory Multi Criteria Analysis (MCA) is employed and described in section 11.1 and 11.2 to understand how coastal adaptation options against flooding are valued by Bonairian stakeholders and experts.

11.1 Applied methods to analyse coastal adaptation measures

This chapter presents the outcomes of the MCA analysis for adaptation measures in Bonaire. First, the applied methods are briefly described. The research phases, as well as methodological steps used for the participatory MCA in this study are based on the generalised MCA phases and steps as defined by Adem Esmail & Geneletti (2017). First, eight coastal adaptation alternatives were selected, including:

- Managed realignment: setback zone;
- Construction restrictions
- Grey: seawall
- Green: mangroves
- Green: coral reefs
- Hybrid: eco-seawall
- Building-level adaptation: dry-proofing
- Do nothing

Second, 11 assessment criteria were defined by means of literature review and expert interviews, which were clustered into four main categories: social, economic, environmental and technical criteria. Third, stakeholders were asked to score the adaptation alternatives on the varying criteria. To evaluate adaptation measures holistically, it is important to take the views of various types of stakeholders into account. The final stakeholder selection includes representatives of various local organisations, as well as representatives of the local community, -businesses, and -government. Later, stakeholders were asked to indicate how relatively important a specific category of assessment criteria is to them in making adaptation decisions. Finally, based on the scores and weights assigned by the stakeholders and experts, the scores were aggregated. The normalised scores for each criterion were multiplied by the relative weight of that criterion, after which all criteria scores were added up for each adaptation option to obtain a final ranking of the most desired adaptation measure according to the Bonairian stakeholders.

11.2 Scores of adaptation alternatives against coastal flooding

11.2.1 Scores

An overview of all individual stakeholder scores per criteria, colour coded by stakeholder type, can be found in Table 11-1, where the individual scores were averaged and normalised to obtain the scores that are shown in Table 11-1.

Table 11-1 Summary of the normalised scores. The colour indicates whether the score is good (green, > 0.67), reasonable (yellow, > 0.33 and ≤ 0.67), or bad (red, ≤ 0.33)

Criterion	Do nothing	Seawall	Eco-seawall	Coral reef restoration	Mangrove restoration	Dry-proofing	Setback zone	Construction restrictions
Acceptability	0.18	0.39	0.50	0.89	0.94	0.63	0.52	0.82
Effect on characteristic appearance	0.50	0.06	0.31	0.88	0.75	0.38	0.94	0.75
Erosion	0.50	0.50	0.63	0.60	0.85	0.50	0.56	0.63
Effect on coral reefs	0.50	0.13	0.33	0.83	0.83	0.50	0.83	0.83
Effect on other habitats	0.50	0.40	0.40	0.70	0.95	0.50	0.80	0.75
Costs	1.00	0.13	0.08	0.50	0.56	0.57	0.44	0.67
Effectiveness	0.00	0.71	0.62	0.48	0.63	0.67	0.94	0.78
Effect on economy	0.5	0.45	0.75	0.88	0.83	0.50	0.38	0.80
Robustness	0.00	0.60	0.67	0.44	0.76	0.67	0.80	0.73
Self-sufficiency	1.00	1.00	1.00	0.00	0.50	1.00	1.00	1.00

The final scores per adaptation option, resulting from the aggregation, can be seen in Figure 11-1. Since the environmental criteria received a high weight from the stakeholders, the scores for these criteria have a relatively more pronounced effect on the final outcome of the MCA than the scores for the other criteria.

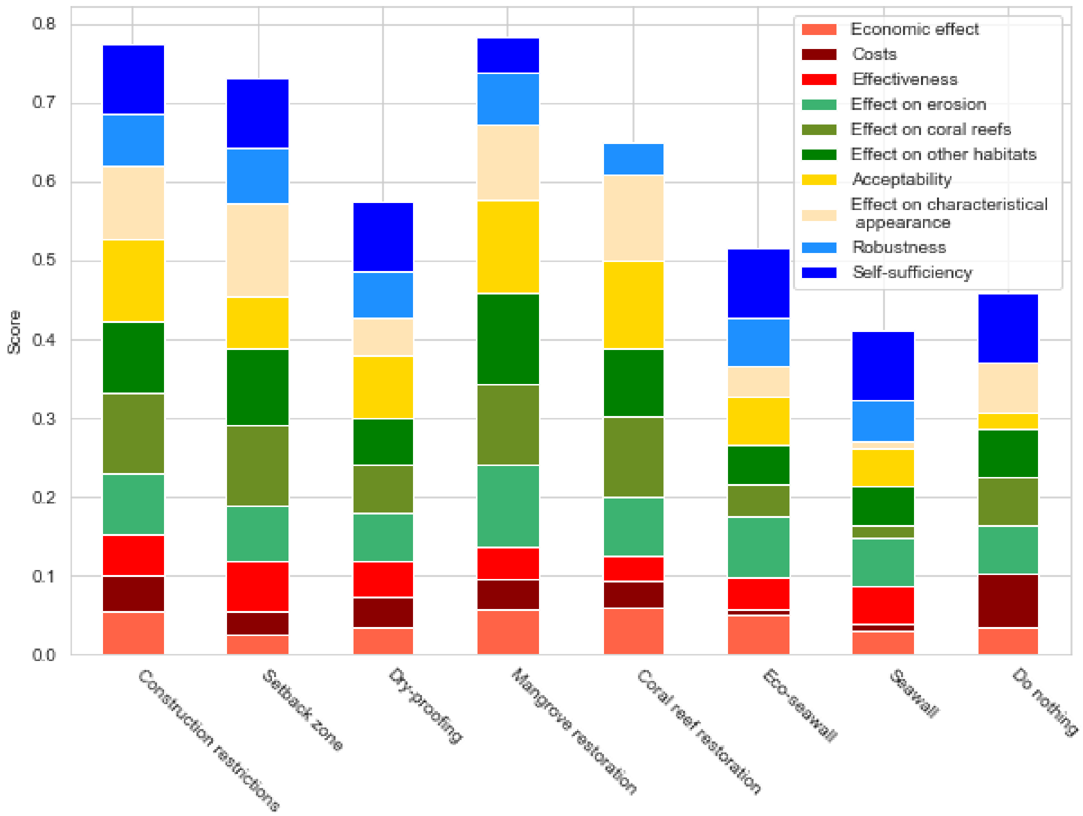

Figure 11-1 Overview the final MCA scores per adaptation option. The colours represent the different criteria: technical (blue), social (yellow), environmental (green), and economic (red).

Combining all the weighted scores per adaptation option results in a final ranking of the measures (Table 11-2). Mangrove restoration and construction restrictions are the two measures that score highest. Both types of seawalls, as well as doing nothing end up at the lower end of the spectrum. Dry-proofing and coral reef restoration both receive an average score, ending up in the middle of the final ranking. The rest of this section will describe the reasoning behind the final scores for each measure.

Table 11-2 Final ranking and total scores of the assessed coastal adaptation options

Rank	Measure	Total score
1	Mangrove restoration	0.784
2	Construction restrictions	0.774
3	Setback zone	0.732
4	Coral reef restoration	0.649
5	Dry-proofing	0.576
6	Eco-seawall	0.515
7	Do nothing	0.460
8	Seawall	0.412

11.2.2 Sensitivity analysis

The sensitivity analysis consists of two parts: the first half of the analysis consist of the stakeholder weights separated per stakeholder group and the second half consists of artificially assigned weights that reflect a strong focus on each of the criteria groups (Table 11-3). The criteria within each category are again assigned equal weights. After the weights are re-assigned, the aggregating step of the analysis is repeated to obtain a new ranking for each sensitivity run.

Table 11-3 Weights applied in each sensitivity run

Type of sensitivity analysis	Sensitivity run	Environmental criteria	Economic criteria	Social criteria	Technical criteria
Weights per stakeholder group	Nature stakeholders	0.45	0.19	0.19	0.17
	Economic stakeholders	0.32	0.16	0.38	0.15
	Culture stakeholders	0.35	0.25	0.22	0.18
	Other stakeholders	0.25	0.25	0.25	0.25
Artificially assigned weights	Environmental focus	0.50	0.17	0.17	0.17
	Economic focus	0.17	0.50	0.17	0.17
	Societal focus	0.17	0.17	0.50	0.17
	Technical focus	0.17	0.17	0.17	0.50

The rankings resulting from the different sensitivity analyses can be seen in Figure 11-2. The results are robust with a wide range of stakeholder preferences and also with adopting a different focus. In the majority of the runs, only the top two measures in the ranking switch places. The only focus that does lead to significant changes in the ranking is the adoption of a technical focus, which results in a significantly lower ranking of the NbS.

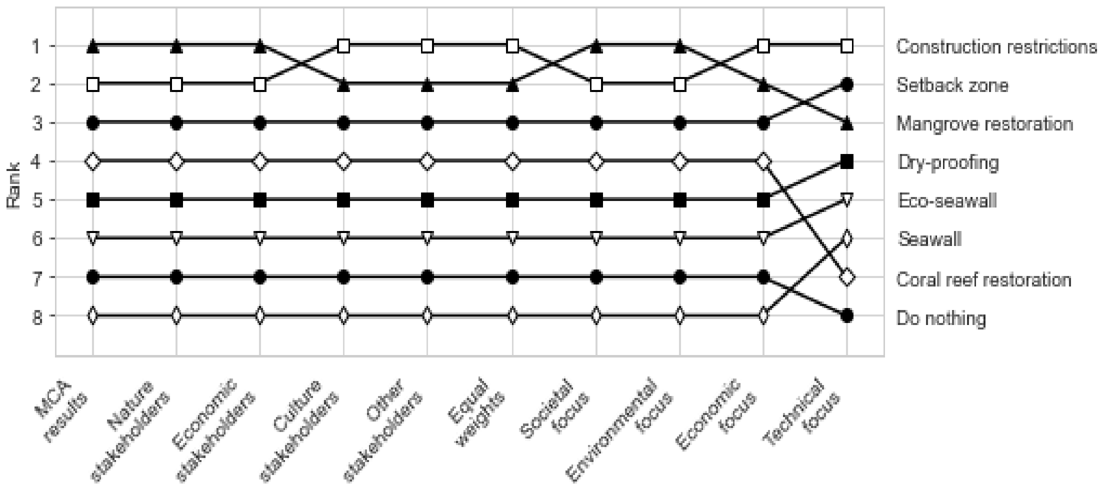

Figure 11-2 Results from the sensitivity analysis.

It is important to note that the MCA depends on stakeholder scores and weights, which means that the final results can be influenced by subjective choices and assumptions made by the stakeholders (Zucaro *et al*., 2021). The costs and effectiveness have, within this study, only been evaluated qualitatively. To develop a robust adaptation plan, it is crucial to conduct a technical assessment of potential adaptation options for different parts of the island and cost-benefit analyses to arrive at a final policy decision (de Bruin *et al*., 2009). This study clearly shows that stakeholders on Bonaire prefer nature-based adaptation options and preventive measures, such as building restrictions in areas that are prone to flooding. However, these measures may not always be effective. First, although mangrove restoration is an option to improve coastal protection in some parts of Bonaire, many urbanised areas are not suitable for such measures. Second, given the results of the flooding analysis in this study, we conclude that even with healthy coral reefs, residential areas are likely to be affected by future floods. The results of the flood risk assessment in our study indicate that some residential areas can already be prone to flooding in the case of high tide events that occur with a frequency of 1/100 years. Compared to most areas in the European part of the Netherlands, such a probability does not result in flooding. Despite the low preferences for hard infrastructure options, such as seawalls, it might still be necessary to implement these measures to protect the people of Bonaire against the effects of climate change.

Aside from increased coastal protection, there are several other things that Bonaire needs to address going forward. These include the several pressures that, according to stakeholders, are vital to address to successfully implement NbS in Bonaire. As previously mentioned, stakeholders have identified Sargassum and erosion as the two major pressures that would need to be addressed for successful mangrove restoration. Both problems are currently already part of Bonaire’s policy plans (ANF *et al*., 2020). In addition to individual adaptation options, future research should investigate the potential of hybrid adaptation solutions, consisting of combinations of measures in one location. Lastly, since a lack of public support can cause significant barriers to the actual implementation of coastal adaptation strategies, it is important to consider the acceptability of adaptation options and how it can be enhanced (Mallette *et al*., 2021).

11.2.3 Adaptation measures against other climatic changes

Besides coastal flooding, climate change causes other changes that pose difficulties for Bonairians, such as rising temperatures and changes in precipitation (see chapter 4). As explained in chapter 4, extreme temperatures are already occurring at an increased frequency and expected to occur with higher intensity in future (Taylor *et al*., 2020; Stephenson *et al*., 2014). In addition, The IPCC noted a trend of declining precipitation during the summer months in the Caribbean (IPCC, 2021). Decreased precipitation and rising temperatures in the Caribbean can lead to a rise in aridity and an increase in the frequency and intensity of agricultural and environmental droughts (Hersbach *et al*., 2020; Debrot *et al*., 2018; IPCC, 2021). This section provides a qualitative description of possible adaptation strategies against heat, erosion and drought.

The consequences of increasing temperatures on the Bonairians are severe and can be fatal if adaptation measures are not implemented. In the literature, there are calls for taking more adaptation measures and developing strategies for protecting people from high-temperature exposure, particularly at night-time (Zhao, 2018; Alcoforado et al., 2015).

Although air conditioning (AC) is regularly promoted as one of the most effective measures to reduce heat stress and heat-related health problems by cooling indoor spaces (Bouchama *et al*. (2007); Anderson & Bell (2009), it comes with various disadvantages and is considered an unsustainable option as the use of AC is resource and energy intensive (Lundgren-Kownacki, 2018), which may further induce increasing temperatures. This will create a negative feedback loop in terms of energy use, increasing heat exposure and the need for cooling options. Moreover, due to the high inflation rates and increasing electricity prices specifically, as well as economic inequality, poorer people may not be able to afford the purchase or running costs of AC. Other, more sustainable options can be found in climate-sensitive building design and alternative cooling technologies (Lundgren-Kownacki, 2018). Climate sensitive building design refers to measures taken in the planning of the urban landscape to the site, the region, and the climate to alleviate negative impacts of climate change (Keitsch 2012). When developing building plans, one should consider the orientation of the building, adequate design of windows, using solar control glazing, making optimal use of prevailing wind direction, applying window blinds, and using reflective surface materials (Verweij, 2022; Givoni 1998).

Furthermore, buildings cannot provide shading when the sun is high. Overhead shading, for example through artificial or natural shading, can to a certain level help to mitigate heat stress by blocking solar radiation and drought by lowering soil temperatures and water evaporation. Building elements, such as overhangs (e.g. vertical fins or balconies), awnings and trellises can provide artificial shading. Natural shading, such as vegetation shading, can be provided by improved natural landscaping management. In addition to providing shading, vegetation also provides additional services, such as filtering water supplies, providing clean air, controlling erosion and, to a lesser extent, flooding, as well as educational and cultural enrichment opportunities.

Estimates of the goat population on Bonaire range between 4,000 to over 30,000, of which the majority of these goats are roaming freely in public lands (Neijenhuis *et al*., 2015). The overgrazing by free-roaming goats through extensive unmanaged husbandry causes desertification and deforestation, which in turn leads to loss of topsoil (erosion), reduced groundwater replenishment, desertification, extinction of plant species and loss of biodiversity, and ultimately a further deterioration of the Bonaire's fringing coral reefs (Slijkerman *et al*. 2019). Even the fish nursery function of coastal ecosystems of Bonaire might be affected by overgrazing of goats (Roberts *et al*., 2017). The weakening of ecosystems on Bonaire could be reversed by managing this unmanaged threat and making nature on Bonaire more instead of less resilient to climate change. The fencing of goats is largely supported by the residents of Bonaire, who also experience serious problems from free-roaming goats that destroy their gardens and kunuku's (Lacle, *et al* 2012). The management of goats would not only generate ecological benefits, but also translate into significant benefits for, among others, the tourism industry (Van der Lely, *et al*. 2013).

12 Conclusion and discussion

12.1 Implications of climate change for Bonaire

12.1.1 Effects in 2050

This study has revealed several implications of climate change for the near future of Bonaire. First, it is clear from the applied flood models that already in 2050 sea level rise and storms will have a significant impact on the low-lying nature reserves of the saliñas, Lac Bay and Klein Bonaire thereby negatively affecting Bonaire through the loss of the valuable ecosystem services they provide (Van der Lely *et al*., 2013; Schep *et al*., 2013). By 2050, the coastline will shift northwards towards the first built-up areas of Belnem. Ranging from the low-end (SSP1-1.9) to the high-end (SSP5-8.5 LC) climate scenario, an area between 3.5 and 4.0 km2 (excluding the saliñas and Lac Bay), respectively, is projected to become permanently inundated due to sea level rise by 2050. This inundated surface area is expected to double due to storm inundation, with an estimated 7.9 and 8.3 km2 of flooded area, respectively.

Second, the analysis of the impact of storm inundation on the built environment revealed that 54 buildings on Bonaire are already vulnerable to coastal flooding risks, with damage costs of around 14 USDm. Since a significant part of the damaged structures are located in the Belnem neighbourhood, flood hazards can have severe local effects and disrupt an entire Bonairian neighbourhood. In addition, by 2050, numerous coastal and southern roads on the island will be unusable under climate scenario SSP 1-1.9, making it impossible for emergency services to reach these areas and buildings.

Third, Bonairian experts and stakeholders identified numerous locations with cultural significance of which in the absence of flood protection measures, a number of them will be permanently inundated or exposed to coastal flood risks by 2050. Loss of cultural heritage may have severe impacts on society, as it may lead to a decline in cultural identity and social cohesion. Hence, it can be concluded that by 2050, the effects of climate change could significantly alter Bonaire's landscape and have severe consequences for its built environment and society if adequate prevention measures are not taken in time.

Fourth, climate change will negatively affect the coral reefs of Bonaire through sea level rise, acidification and increasing temperatures. The overall reef health index declines in three of the four all climate scenarios by 2050 and beyond. This loss of coral reefs will further amplify storm inundation and thus lead to an increase in the inundated areas and inundation depth. . Coral reef degradation will affect tourism and, hence, the economic development of various sectors of Bonaire. Under SSP2-4.5, SSP3-7.0, and SSP5-8.5, a reduction in dive tourist arrivals is estimated to be 17 thousand, 55 thousand, and 118 thousand by 2050, respectively.. This may cause a contraction in Bonaire’s GDP ranging from 27 USDm under SSP2-4.5 to 174 USDm under SSP5-8.5 by 2050. In the most pessimistic scenario, Bonaire could experience an economic contraction of 25%, which would have significant socio-economic implications for the island’s inhabitants.

Fifth, despite the fact that climate scenarios and time scales are not fully implemented into the assessment of climate change's effects on public health and intangible heritage, our findings reveal significant impacts in these domains. Local experts report a range of effects of climate change on Bonairians' health, such as changes in vector-borne disease incidence and heat-related stress. Several of these effects are already observed on the island and will continue to influence Bonaire's public health. This confirms the fact that climate change is not an issue of the distant future, but rather one that is already occurring. Due to a predicted increase in the older population, Bonaire's population will become even more susceptible to heat-related stress disorders. Given the rising temperatures, this will lead to more severe and potentially lethal impacts.

12.1.2 Effects in 2150

When considering the predicted effects and consequences of climate change for Bonaire in the long term, even more severe outcomes are anticipated. Not only is the climate effects more significant, also the the variations in flooding and impacts associated with the different climate projections are much more pronounced in 2150 compared to 2050, given the larger uncertainty of long term modelling

With a predicted permanent inundation area of 9.4 km2 for SSP 1-1.9 and 29.2 km2 for SSP5-8.5LC, respectively, the shoreline of Bonaire is expected to change drastically. Depending on the climate scenario, coastal storm inundation will further expand the flooded regions, which will range from 14.3 km2 to 32.2 km2 in size. From this point in time, storms are expected to largely affect Kralendijk under an SSP5-8.5 scenario, resulting in an estimated damage cost value of 317 USDm. As permanently inundated buildings are not included in the estimated damage costs projections, the presented damage costs values are likely to be on the conservative side. The flood analysis clearly identifies Bonaire's high-risk areas: Belnem and Kralendijk.

In addition to buildings, tangible cultural heritage is also predicted to be significantly impacted. For example, under all scenarios in 2150, there is a high probability that the tangible cultural heritage on the Southern tip of the island, such as the salt pans, slave huts, obelisks, lighthouse, and flamingo sanctuary among others, will be inundated and damaged due to permanent and storm inundation.

Although not being quantitatively analysed, it can be expected that the increase in warm days and warm nights and an increase in consecutive hot days (or warm spells) in 2150 will exacerbate heat-related stress, disorders and mortality. Climate change may also negatively affect public health in indirect ways, such as physical and emotional damage within the Bonairian population caused by more severe storms.

Overall, we conclude that climate change is likely to have severe consequences on Bonairians' safety, livelihoods and general wellbeing. Since our study did not include all effects of climate change and since climate research with regional and local precision is still in development, the impacts presented in our study can be regarded as preliminary lower-bound estimates. In other words, additional research is likely to generate estimates of more severe impacts of climate change in Bonaire, as opposed to milder impacts.

To protect the people of Bonaire from the most harmful effects of climate change, adaptation techniques against a variety of climate change effects must be further investigated, and implementation strategies must be developed and executed soon. Adaptation strategies should include, for instance, the conservation of coral reefs and the prevention of heat exposure and erosion in addition to the prevention of coastal and pluvial floods. Furthermore, although the impacts of climate change necessitate immediate action, decision-makers should not only focus on the present or 2050, but rather on a longer time-period, such as 2150 and beyond, as the effects of climate change will significantly worsen.

12.2 Implications of this study for the other Islands in the Dutch Caribbean

Not much is known yet about the impact of climate change on human safety, livelihoods and general wellbeing in the Dutch Caribbean. This study is the first attempt to map and quantify a broad range of climate change effects for Bonaire. As such, it is relevant to reflect on the implications of this study for other islands in the Dutch Caribbean. This is particularly true for the Leeward Antilles (Aruba and Curaçao), given their biophysical, climatic and socio-economic similarities.

The broad scope of this study, which considers biophysical as well as socio-economic elements, required us to collect and combine a wide range of data. Where possible, we used existing information, but as is common for most small islands (Van Beukering *et al*. 2007), various information gaps forced us to improvise in generating credible evidence by applying alternative data collection methods. Such methods included participatory mapping in detecting cultural heritage on Bonaire, neighbourhood field sampling to validate infrastructural information and the analysis of social media information to identify ecosystem services hotspots on the island. As these methods are generally less costly to implement, they are suitable for application in a small island setting which is characterised by limited funds and capacity. When conducting research in data-scarce regions, such as various Caribbean islands, researchers could learn from and apply these innovative data collection and assumption approaches to fill data and knowledge gaps.

When looking at the climate trends and the temperature increase, decreasing rainfall patterns and sea level rise specifically, it can be concluded that all six Caribbean islands in the Dutch Kingdom are subject to similar climatic changes. In terms of extreme weather events, the projections are more uncertain. If, however, the frequency and intensity of tropical storms increase, it is likely that the northern islands (St Maarten, Saba and St. Eustatius), which are located in the hurricane belt, will be more affected compared to the southern islands (Aruba, Bonaire and Curaçao).

How these climatic changes affect ecological conditions will differ between islands. Since Aruba and Curacao are most comparable to Bonaire in terms of climatic conditions and ecosystems, increased drought is likely to have similar effects on the terrestrial ecosystems on these islands. The northern islands have distinct ecological features, which make these islands difficult to compare. With regard to the increases in seawater temperature, the effects are expected to be similar on all six islands. The implications for coral reef degradation, however, can differ. Coral reefs on Bonaire are currently in a relatively better condition compared to the other Caribbean islands of the

Netherlands and the Dutch Kingdom, with the exception of certain areas in Curaçao (Jackson *et al*., 2014). As such, it is expected that the reefs of Bonaire are more resilient to the effects of climate change.

Flood risk strongly depends on the level of development and geographical characteristics of each island. Curacao, Aruba and St Maarten have substantial urban areas that are not far above sea level. In addition, these islands are more densely populated, with larger urban areas and more infrastructure. This implies that the exposure to flood risk is also present on these islands. Based on the results of this study, however, it is difficult to draw conclusions about the order of magnitude of potential flood damage. This would require a similar analysis of flooding scenarios and associated flood risk as was conducted in this study, which was performed on St Maarten (Maas, 2022). In this study, it was found that one out of seven buildings in St Maarten are at risk of flooding in different climate scenarios, with total damages ranging between US$293 million and US$312 million.

The effect of coral reef degradation on tourism revenues depends strongly on the composition of the tourism industry. Although tourism is an important economic pillar on all islands in the Dutch Caribbean, Bonaire depends relatively more on dive tourism. This implies that Bonaire's tourism industry is more vulnerable to coral reef degradation. Nevertheless, there are also other climate change effects that have implications for tourism. Heat stress and higher frequencies of tropical storms also have the potential to reduce tourist arrivals. After hurricane Irma, for example, the tourism industry on St Maarten took multiple years to recover. More detailed analysis of the respective tourism sectors is required to draw conclusions for other islands.

The analysis of health effects in this study has been largely based on regional studies in the Caribbean. Most health effects are expected to be quite similar across the Caribbean, especially those related to increased heat stress. Mental health conditions related to extreme weather events, however, might be more prone on the islands in the hurricane belt. The effects on cultural heritage, on the other hand, are strongly dependent on the specific locations and traditions. Tailored research would be required to identify the effects on cultural heritage on each island.

12.3 Limitations of the study and suggestions for future research

This study presents a unique overview of climatic and human impacts of climate change on the island of Bonaire and adaptation alternatives, but it also has some limitations. The different components of the study came with various challenges and uncertainties. In this section we will focus on the most significant and overarching uncertainties and limitations of the study.

First, although research on anthropogenic climate change is now well established (IPCC, 2021), climate change modelling comes with various uncertainties. After all, any model which utilises numerical modelling comes with different sources of uncertainty (Foley, 2010). Since climate systems and the models to determine their direct risks to communities and the economy are composed of numerous complex processes and interactions, no model can ever be expected to perfectly simulate this. For example, the ecological module used to predict future changes in Bonaire's coral reefs rests on the assumption that the interactions between ecosystem properties and climate pressures can be quantified in linear relationships. However, coral reefs are dynamic and heterogeneous systems that will respond non-linear according to environmental changes (Wolfe & Roff, 2009). The models employed in this study (i.e. climate models, inundation models, ecological models, economic models), are interlinked and layered within this study. This can result in a cascade of uncertainties that accumulate with each subsequent analysis, leading to a wide range of predicted hazards and impacts.

The absence of certain types of (high-quality) data was an additional significant limitation that contributed to the levels of uncertainty in all the components of the study. Existing data were utilised whenever possible, but data gaps necessitated the use of alternative data collection methods. When examining the available data to determine climate trends and inundation risks, it became apparent that certain data were absent, imprecise, or of questionable reliability. The data for the European Netherlands appears to be significantly more accessible and accurate than the data available for the Caribbean Netherlands. This discrepancy in data availability between Caribbean Netherlands and European Netherlands is confirmed by the following examples below.

In the current study, modelled storm tracks were applied due to a lack of historical data. Similarly, due to the lack of a multi-year accurate time series of temperature on Bonaire, the KNMI (2021) estimated the past temperature trend of Bonaire using the time series of Curaçao. Moreover, the FABDEM dataset, based on satellite data, applied in this study has a spatial resolution of 30 metres, which is significantly less accurate than the 0,5 metres resolution DEM used in the European Netherlands, which is generated from very high-resolution LiDAR data. Accurate elevation data are crucial inputs for geosciences and other disciplines (Hawker, 2022). For example, Vousdoukas *et al*. (2018) showed that a change in resolution from 10 to 100 metres could change the estimated expected annual damages by 200%. Self-measured elevation points and those from Geomaat Bonaire (geodetic engineering company) were found to differ significantly from the FABDEM, with an average overestimation of the elevation of 1,2 metres based on 16 data points. This overestimation is substantial when comparing it to the SLR projection of 1,45 metres under the high-end SSP5-8.5 scenario for 2150. The inaccuracies in the elevation map may significantly influence and potentially result in a substantial underestimation of the inundation results. Thus, a more accurate DEM is required for Bonaire to provide more certain inundation results and better understand the climate change risks for the population.

While performing the analysis on the built environment, a number of issues arose in order to properly conduct an analysis comparable to the situation in the European Netherlands. There is a large discrepancy in data availability between Caribbean Netherlands and European Netherlands. For example, in the European Netherlands the “Basisregistratie Adressen en Gebouwen” (BAG) is available which contains geospatial information of each building in the European Netherlands, including its use. This information is freely available for everyone in the European Netherlands, but for Bonaire, this information is not available at all. For critical infrastructure (i.e. roads, electricity and water supply), the analysis would rely in both the Caribbean and European Netherlands mostly on publicly available information through OpenStreetMap. However, the information for the European Netherlands is much more complete and better validated. Lastly, Bonaire lacked nearly all the data necessary to conduct a risk analysis on its electricity and water systems.

A lack of data affects the Input-Output model as well. Bonaire fundamentally lacks publically available and contemporary economic data (Schep *et al*. 2013). The year 2017 was used as the base year in the model, as it was found to have the most complete dataset in terms of economic and ecological information of Bonaire. However, multiple variables had to be retrieved from earlier years and corrected or estimated for 2017 to fill in gaps in the data. For instance, the SUT table for 2017 was updated using the SUT table of 2012 by Koks & van Zanten (2015) due to a lack of publicly available data on sectoral output in Bonaire. Thus, diverse and up to date datasets can be vital to further strengthen the predictive power of the ecological module and the input output model that was developed in this study.

When looking at the availability of data related to health, there appears to be a scarcity of information regarding the mental health status of Bonairians, particularly adolescents. This is remarkable given the extent to which the European Netherlands has invested in this field of research type of study aimed at young people (UNICEF, n.d.). Furthermore, it was found that research has mostly been performed on the climate change impacts on health in the Caribbean region, but not for Bonaire specifically. Although health experts assumed that the research on climate change and health in the Caribbean is transferable to Bonaire, the individual Caribbean islands still experience different climates. Hence, there will be unique differences in the climate experiences of the different countries and islands, which might result in different climate change impacts on health.

The multi-criteria analysis applied in this study is based on input from local stakeholders. Although local environmental, economic and cultural experts were able to provide valuable input for the evaluation of coastal adaptation options on Bonaire, local expertise and knowledge regarding flooding and adaptation options is lacking. Due to the aforementioned limitations, conclusions and interpretations should be approached with caution.

Lastly, we acknowledge that ongoing research into climate models, and their outcomes, might alter the results found in this study. This primarily has to do with the way the El Niño Southern Oscillation is represented in climate models. Research has shown that our current generation of climate models has a tendency towards simulating more El Niño-type of climate conditions towards the future, whereas observations are indicating that the climate is moving more towards La Niña conditions (Seager et al., 2019, Broton Blanes, 2022). These climate conditions have significant impacts on atmospheric conditions in the Caribbean Sea. During an El Niño event, tropical cyclone activity in the Caribbean Sea is suppressed compared to average conditions. On the contrary, during a La Niña event, tropical cyclone activity is enhanced compared to average conditions, hereby elevating the potential risks associated with this hazard. Furthermore, El Niño events typically cause drier-than-average conditions over the Caribbean region (i.e., less precipitation); La Niña events, on the other hand, cause wetter-than-average conditions, elevating flood risk from precipitation. Combining this information, this means that the future tropical cyclone and precipitation risks presented in this study might be on the conservative side, as the climate models used here almost certainly contain this El Niño tendency. Therefore, we recommend further research into these climate model biases and their implications for climate risks in the Caribbean.

13 Recommendations

This study provides the first holistic assessment of the environmental and economic effects of climate change on Bonaire. Although it is complicated to draw definite conclusions about the magnitude of the impacts of climate change, it is clear that significant climate change impacts are anticipated in Bonaire and that some effects, such as heat stress and coral bleaching, have already occurred. Coastal inundation is predicted to damage the built environment, infrastructure and tangible cultural heritage, and may cause physical and mental health issues. Degradation of coral reefs will not only exacerbate storm flooding but will also have detrimental effects on Bonaire's economic growth. Local stakeholders conducted a preliminary evaluation of nature-based solutions most suitable against coastal flooding, calling for further investigation on their efficacy and feasibility. The findings of this study are not only applicable and relevant for Bonaire but may also be transferred to other Dutch and non-Dutch Caribbean islands. Nevertheless, recognising geographical and cultural diversity, it is recommended that other low-lying SIDS also evaluate the impacts, vulnerability and adaptation options against climate change hazards through primary research.

This study can serve as a foundation for stakeholders to develop and implement effective responses. We strongly recommend further steps to be taken to protect the Bonairians against the negative effects associated with climate change. For example, the identified inundation areas need to be taken into account in developing future zoning and construction plans. Moreover, the Dutch government and local authorities should implement coastal adaptation measures to protect at-risk communities and tangible cultural heritage from coastal flooding hazards.

However, to reduce uncertainties and make better-informed decisions on acceptable and effective protective measures, it is necessary to have a deeper understanding of the effects of climate change and adaptation strategies, which extend beyond flooding and coral reef deterioration. Currently, the findings should be taken with caution and future studies are needed to improve and confirm the findings. Therefore, it is recommended to improve the quality and availability of relevant data. For example, a more accurate elevation map is beneficial in predicting more precise flood hazards. Therefore, a high-resolution and high-precision DEM should be developed for Bonaire and relevant data (e.g. about infrastructure, network systems and economic development) must be updated and/or made publicly available. In addition, we recommend that future research concentrates on other ecological climate change-induced alterations, such as erosion and drought, as well as appropriate adaptation strategies against those changes. Furthermore, the brief overview of possible adaptation methods against heat and droughts must be broadened and further investigated, for instance by quantitatively evaluating their attractiveness, effectiveness, and practicability. This study should also be complemented with a quantitative analysis, such as a cost-benefit analysis, to determine the feasibility and effectiveness of the proposed and ranked coastal adaptation options. Finally, when more information is available, it is recommended to develop an efficient and equitable flood management for Bonaire, based on reliable flooding standards.

Finally, decision-makers at all levels of governance must consider how the potential impacts of climate change can be mitigated or managed. Decision-makers should develop communication strategies for discussing the effects of climate change and potential solutions with the population of Bonaire. The importance of education and involvement of the local community for the social acceptability of policy decisions, regardless of the specific measure that will be implemented, became apparent in this study. We recommend employing a participatory communication strategy in which not only theoretical knowledge but also indigenous adaptation solutions can be discussed, with the aim of raising the island's protection against climate change to levels that are equivalent to those that are applied for the rest of the Netherlands, and that of other at-risk coastal communities.

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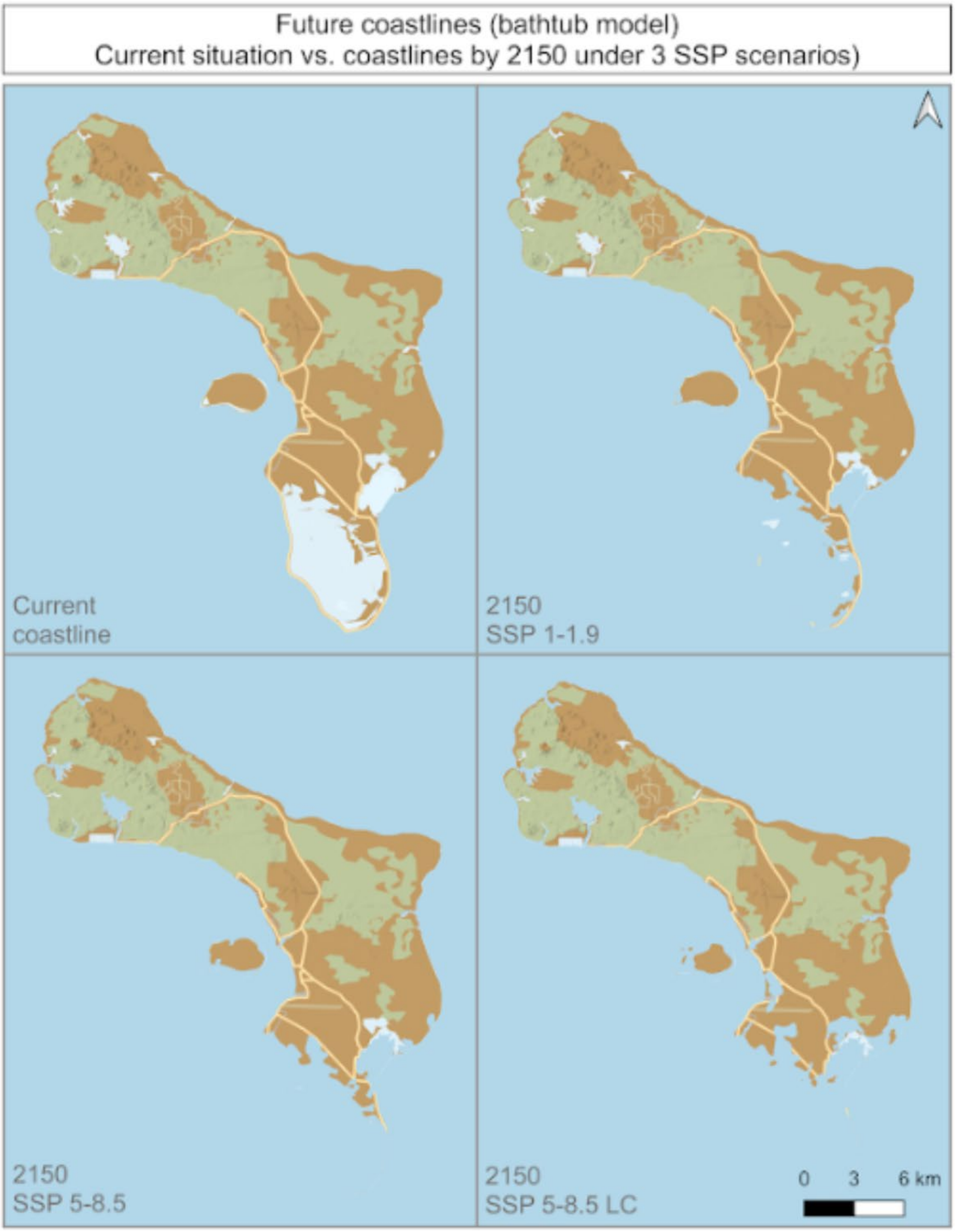
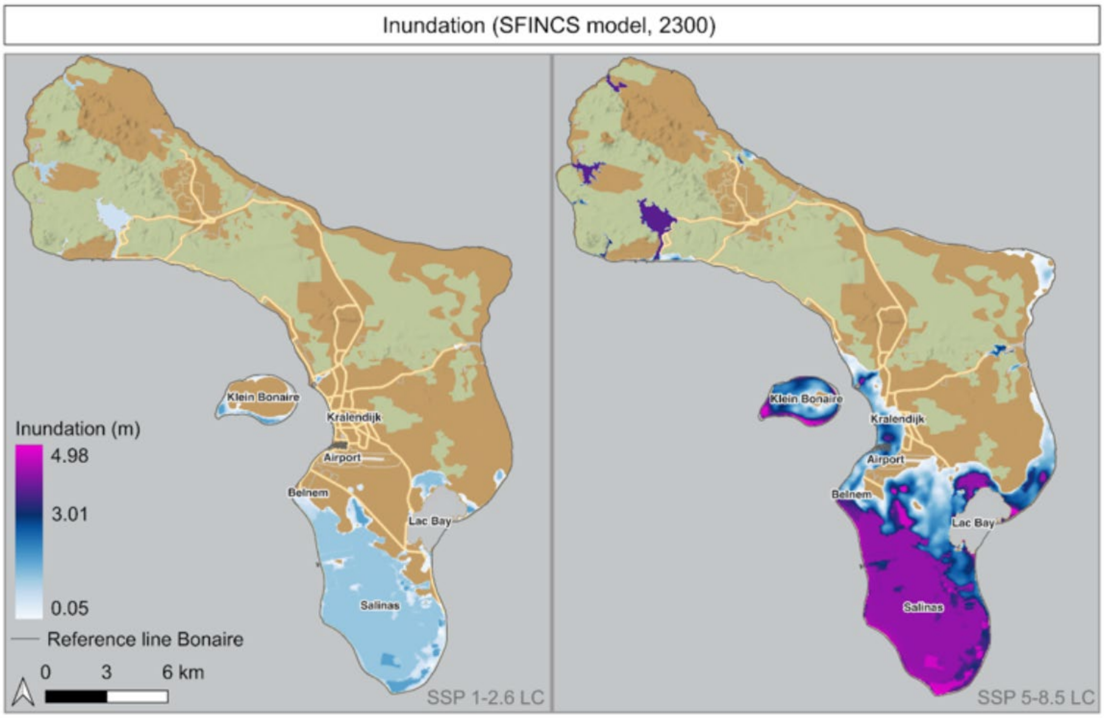
Appendix A Future coastlines (bathtub model) under climate scenarios SSP1-1.9, SSP5-8.5 and SSP5-8.5 LC in 2150



Appendix B Inundation (SFINCS model) under climate change scenarios SSP1-2.6 LC and SSP5-8.5 LC in 2300



Appendix C Identified cultural heritage

1. Boka Slagbaai

2. Washington Slagbaai

3. Playa Frans

4. Gotomeer

5. Dos Pos

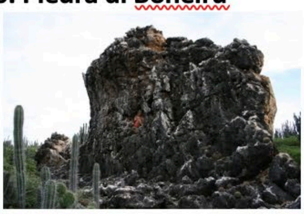
6. Landhuis Karpata

7. Lourdes Grotto

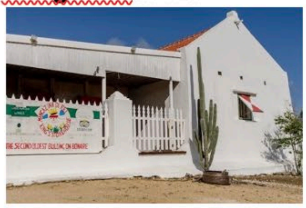
8. Rincon

9. San Ludovico catholic church

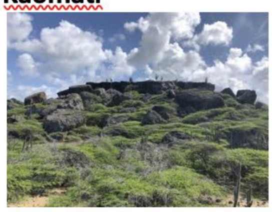
10. Piedra di Boneiru



11. Mangazina di Rei



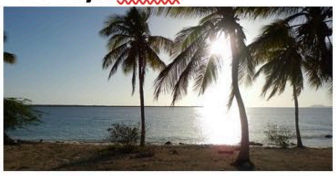
12. Kaomati



13. Boka Onima

14. Indian inscriptions

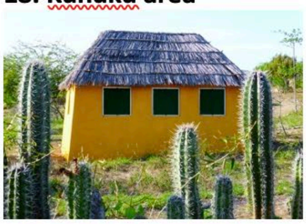
15. Playa Lechi



16. Hofi Kultural

17. Antriol

18. Kunuku area



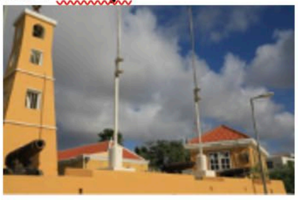
19. Lagun

20. Playa

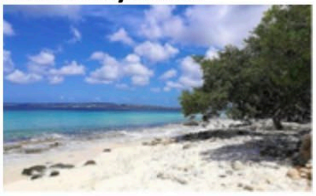
21. Plasa Machi Mimi

22. Bestuurskantoor

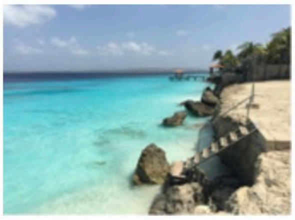
23. Fort Oranje



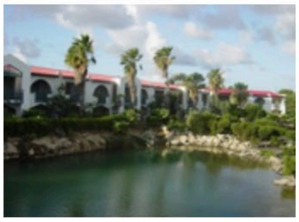
24. Donkey Beach



25. Bachelor's Beach

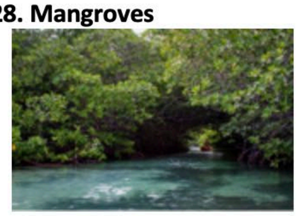


26. Tera Kora



27. Sorobon

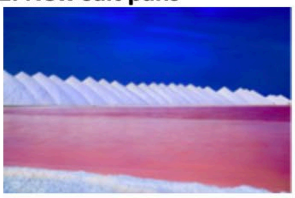
28. Mangroves



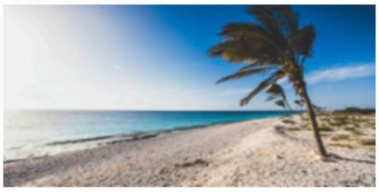
29. Lac Cai

30. Blue obelisk

31. New salt pans



32. Pink Beach



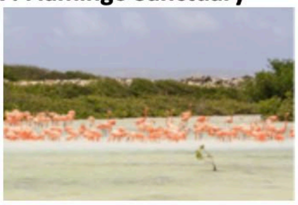
33. White obelisk

34. White slave huts

35. Old salt pans

36. Atlantis fishermen's hut

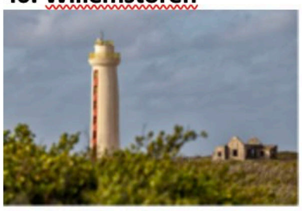
37. Flamingo Sanctuary



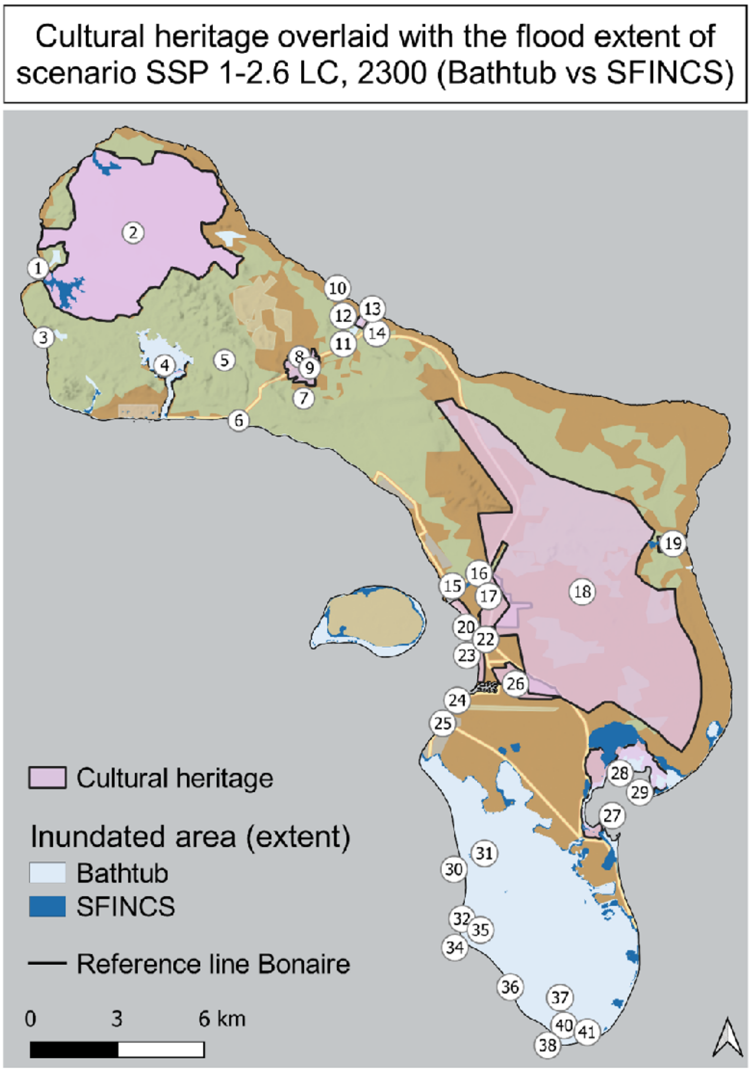
38. Red obelisk

39. Red slave huts

40. Willemstoren

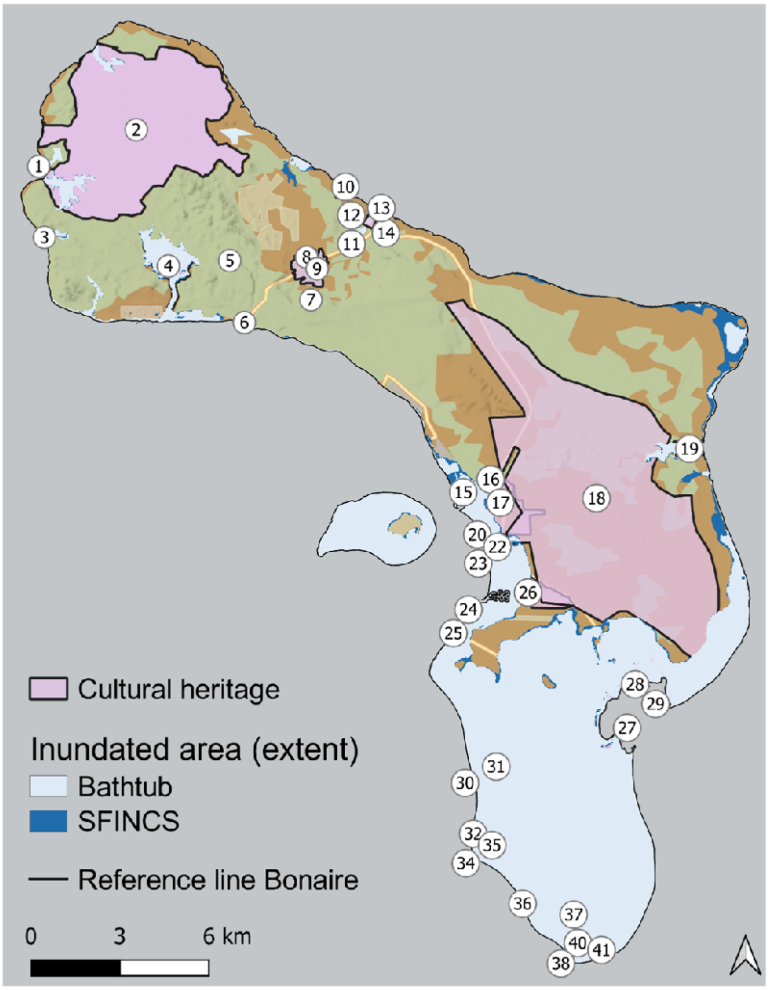


Appendix D Cultural heritage overlaid with the flood extent of SSP1-2.6 LC and SSP5-8.5 LC in 2300



1	Boka Slagbaai
2	Washinton Slagbaai
3	Playa Frans
4	Gotomeer
5	Dos Pos
6	Landhuis Karpata
7	Lourdes grotto
8	Rincon
9	San Ludovico catholic church
10	Piedra di Boneiru
11	Mangazina di Rei
12	Kaomati
13	Boka Onima
14	Indian inscriptions
15	Playa Lechi and tamarind tree
16	Hòfi Kultural
17	Antriol
18	Kunuku area
19	Lagun
20	Playa
21	Pasa Machi Mimi
22	Bestuurskantoor
23	Fort Oranje
24	Donkey Beach
25	Bachelor's Beach
26	Tera Kòrá
27	Sorobon
28	Mangroves
29	Lac Cai
30	Blue obelisk
31	New salt pans
32	Pink Beach
33	White obelisk
34	White slave huts
35	Old salt pans
36	Atlantis fishermen's hut
37	Flamingo Sanctuary
38	Red obelisk
39	Red slave huts
40	Old salt pans
41	Willemstoren

Cultural heritage overlaid with the flood extent of scenario SSP 5-8.5 LC, 2300 (Bathtub vs SFINCS)



1	Boka Slagbaai
2	Washinton Slagbaai
3	Playa Frans
4	Gotomeer
5	Dos Pos
6	Landhuis Karpata
7	Lourdes grotto
8	Rincon
9	San Ludovico catholic church
10	Piedra di Boneiru
11	Mangazina di Rei
12	Kaomati
13	Boka Onima
14	Indian inscriptions
15	Playa Lechi and tamarind tree
16	Hòfi Kultural
17	Antriol
18	Kunuku area
19	Lagun
20	Playa
21	Pasa Machi Mimi
22	Bestuurskantoor
23	Fort Oranje
24	Donkey Beach
25	Bachelor's Beach
26	Tera Kòrá
27	Sorobon
28	Mangroves
29	Lac Cai
30	Blue obelisk
31	New salt pans
32	Pink Beach
33	White obelisk
34	White slave huts
35	Old salt pans
36	Atlantis fishermen's hut
37	Flamingo Sanctuary
38	Red obelisk
39	Red slave huts
40	Old salt pans
41	Willemstoren