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RESEARCH

An Integrated Assessment of Climate Change Impacts and Implications on Bonaire

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Abstract

Bonaire's topographic and geographic characteristics, in combination with the island's high dependency on economic sectors that are susceptible to the impacts of climate change, make this Caribbean island particularly vulnerable to climatic changes. In this study, biophysical and economic models are combined and complemented with stakeholder consultation to assess and quantify environmental effects and associated socio-economic impacts of climate change on Bonaire. We apply three climate scenarios of the 2021 IPCC report (SSP1-2.6, 2–4.5, and 5–8.5) and combine them with local conditions to conduct a site-specific integrated assessment. The results show that various buildings, critical infrastructure, and identified tangible cultural heritage, especially at the south of Bonaire, are at risk of climate change induced coastal inundation by 2050, even under the least severe climate projection. In addition, the overall health of coral reefs declines under the climate scenarios SSP2-4.5 and SSP5-8.5 due to sea level rise, acidification, and increasing temperatures. In the most pessimistic scenario, Bonaire could experience a reduction in dive tourist arrivals of 118,000, which can lead to an economic contraction of 174 USDm (25%) in Bonaire's GDP. In the absence of timely planning and implementation of adaptation measures, the impacts of climate change may have serious implications for inhabitants' lifestyles and wellbeing. These results are imperative for various stakeholders, and stress that decision-makers should focus on the development and implementation of effective and feasible adaptation strategies urgently. Moreover, future researchers confronted with data scarcity in comparable contexts can utilise the novel methodologies employed in this study.

Keywords Climate change assessment · Caribbean · Dynamic flood modelling · Cultural heritage · Coral reef degradation · Input–Output model

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Introduction

Climate change is a leading concern of our time as it is projected to negatively impact economies, communities, and ecosystems (Tol 2018; Walther 2010). Small islands are at the front of the most vulnerable regions at risk of climate change because of their fragile ecosystems, small economies, and often extensive, low-lying coastal areas (Carabine and Dupar 2014; Macpherson and Akpinar-Elci 2013). Therefore, these islands are expected to suffer excessively from temperature increases, changes in precipitation, sea level rise (SLR), coral bleaching, tropical cyclones, droughts, and floods (IPCC 2022). Moreover, small islands are disproportionately affected by climate change compared to their negligible contribution to global warming (Thomas and Benjamin 2020).

Due to its topography and geography, the Caribbean region is one of the most vulnerable to the effects of climate change (Lal et al. 2002; Mimura et al. 2007). Moreover, the Intergovernmental Panel on Climate Change (IPCC) predicts higher temperatures, SLR, and changing precipitation patterns for the Caribbean region (Akpinar-Elci and Sealy 2014; Nurse et al. 2014). These projected changes will produce environmental, economic, and social damage and put further pressure on small Caribbean islands. However, despite the widespread conviction that anthropogenic warming will have serious effects on an island's environment and inhabitants (Akpinar-Elci and Sealy 2014), the exact impacts of climate change under various climate projections are limitedly studied. This results in high uncertainty about the environmental changes that will occur, the direct physical risks posed to people and communities, and the consequences for their lifestyles and well-being.

Bonaire is one of the small Caribbean islands considered particularly vulnerable to anthropogenic factors, such as climate change (Baban 2003; Taylor et al. 2012). The island, which has been a public entity within the Netherlands since the Netherlands Antilles dissolved in 2010, is located 80 km north from Venezuela and has a surface of 288 km^2 plus another 6 km^2 for the adjacent island of Klein Bonaire (see Fig. 1). Bonaire has a predominantly low-lying terrain, which is covered by low thorny vegetation (Uyarra et al. 2005). The waters surrounding Bonaire and its satellite island, Klein Bonaire, are 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

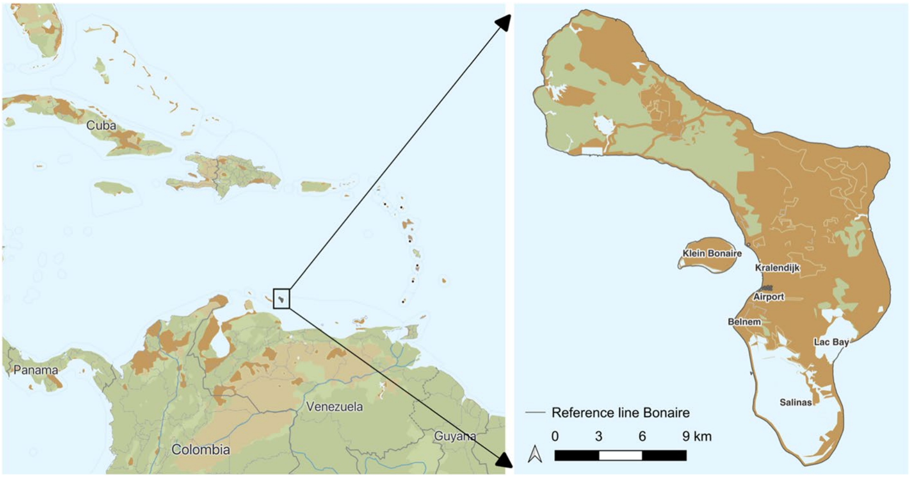

Fig. 1 The Dutch Caribbean Island of Bonaire, located in the Caribbean Sea

(Uyarra et al. 2005), as scuba diving is tourists' primary mainstay activity. It was estimated that in 2012, the direct GDP from tourism amounted to 16.3% of total GDP (Statistics Netherlands 2012), but it should be noted that Bonaire's tourism sector is a far-reaching system that serves growth in other vital industries (Schep et al. 2013). However, this also implies that Bonaire's local economy is heavily dependent on external rather than domestic resources and, 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). As with other areas in the Caribbean, the reefs around Bonaire have suffered from increased pressures from climate change, such as rising coral mortalities due to bleaching events and diseases (Spalding et al. 2001), and local pressures, such as erosion and nutrient loading.

This loss of healthy coral reefs will not only affect the attractiveness of Bonaire as a travel destination and influence tourism demand, but may indirectly result in socio-economic impacts that affect the quality of life on the island, including health, natural resources, coastal protection, water and food security, and employment opportunities (Rhiney 2015; Taylor et al. 2018). Furthermore, other effects of climate change, such as gradual changes in SLR, the intensity of storm surges, and the occurrence of extreme events, may directly jeopardise public safety and the built environment. Due to the fact that large parts of the island are low-lying, Bonaire's built environment and tangible cultural heritage are specifically exposed to storm surges and coastal flooding.

Recent years have seen a spike in studies addressing the impacts of climatic stressors and assessing associated socio-economic impacts (Sesana et al. 2021). For example, various studies examine the direct inundation damage costs of SLR to infrastructure such as buildings and roads (e.g. Chinowsky and Helman 2021; Lin et al. 2014). Other studies, on the other hand, have addressed the threats posed by SLR on cultural heritage, of which some target islands specifically (e.g. Ravanelli et al. 2019; García Sánchez et al. 2020; Ezcurra and Rivera-Collazo 2018). Burke and Maidens (2004), for example, estimated that direct economic damage in the Caribbean region ranges from 350 to 870 USDm per year, while indirect losses resulting from losses in fisheries, dive tourism, and the need for additional shoreline protection services amount to 3 USDb to 4 USDb per year. However, most of these studies generally concentrate on one single phenomenon of climatic change, such as SLR, droughts, or coral reef degradation, and their socio-economic implications.

As opposed to existing literature, this study examines multiple socio-economic impacts of climatic change and the challenges of adaptation on a small island. By doing so, this study aims to assess various socio-economic impacts of anthropogenic warming on Bonaire by focusing on (I) economic losses due to coral reef degradation and (II) damages to buildings, critical infrastructure, and tangible cultural heritage due to coastal flooding by 2050. By means of a risk modelling framework, the environmental changes and associated consequences for the island of Bonaire are examined under various climate projections. First, the expected environmental changes associated with different climate projections, such as levels of coastal inundation, coral degradation, and temperature changes, are determined. Second, the expected socio-economic implications associated with the climatic changes are predicted, including impacts on the economy through reduced tourism demand, damages to the built environment, and the expected loss of cultural heritage. The results will indicate whether and what type of action is needed to protect the island of Bonaire and its inhabitants against the implications of climate change. In addition, this paper provides several policy recommendations for local and national authorities, including the necessity and location of coastal adaptation measures to safeguard the local community, infrastructure, and cultural heritage. Moreover, this study applies various innovative research methods and could therefore serve as a basis or inspiration for various other data-scarce islands being at risk of climate change.

The paper is structured as follows: Sect. 2 describes the study's methodological approach, including its strategy to data collection, modelling and analysis. The findings of the analyses are presented in Sect. 3. The discussion in Sect. 4 puts the findings of this paper in perspective to other studies and reports this study's limitations and opportunities for future research. Section 5 concludes.

Methods

To assess the impacts of climate change on Bonaire, a traditional risk approach was applied, in which risk is defined as the function of hazard – the probability of a flood event or coral reef degradation; exposure—the population and value of assets subject to flooding; and vulnerability— the capacity of a society to deal with the event (UNDRR 2015). Figure 2 shows the methodological strategy that has been applied for the integrated assessment of climate change impacts on Bonaire.

Hazard

To evaluate the effect of climate change on coastal flooding and coral reef degradation on the island of Bonaire, the following methodological steps were undertaken: First, different SLR projections for the year 2050 and the impact of storm events on coastal inundation were evaluated by dynamically incorporating storm tide and waves into a coastal inundation model. In addition, the influence of climate change-induced coral reef degradation on the inundation extent was assessed. A visual representation of the input data, consulted databases, applied research methods, and expected output can be found in Appendix A.

Sea Level Rise and Coastal Flooding

Coastal inundation was simulated using SLR projection, storm tides, wave setup, a Digital Elevation Model (DEM), and implications of coral reef deterioration.

The (NASA) IPCC AR6 Sea Level Projection Tool (2021) was consulted to acquire SLR projections for Bonaire in 2050. This tool forecasts global SLR from 2020 to 2150 based on the AR6 IPCC report's Shared Socioeconomic Pathways (SSP) scenarios, describing alternative socioeconomic developments (Garner et al. 2021; IPCC 2021). To investigate a wide range of possible futures for Bonaire, we look at three SSP-RCP scenarios: SSP1-2.6 is the applied low-end scenario, followed by SSP2-4.5 and SSP5-8.5 as the medium- and high-end scenarios, respectively. Whereas the first scenario depicts a drastic reduction of global CO2 and net-zero by 2050, in the second scenario CO2 emissions hover around current levels before starting to reduce mid-century, and in SSP5 at the upper end of the range, CO2 emissions levels roughly double by 2050. For every SSP SLR projection, the quantile was taken as the SLR value modelled in this study. Spatially, the projections of the grid cell where Bonaire is located are: 12°–13°N; 68°–69°W.

Storm tide data was retrieved from the COastal dAtaset of Storm Tide Return Periods (COAST-RP) dataset (Dullaart et al. 2021). This is a global dataset with storm tide levels corresponding to ten different return periods (RPs), ranging from 1 up to 1000 years. For the storm tide data of Tropical Cyclones (TCs), the Synthetic Tropical cyclOne geneRation Model (STORM) model by Bloemendaal et al. (2020) was applied to 38 years of historical TC data from the International Best Track Archive for Climate Stewardship (IBTrACS), to statistically extend this dataset to 10,000 years of TC activity. Subsequently, the synthetic tracks from the STORM dataset were utilised as forcing for the hydrodynamic Global Tide

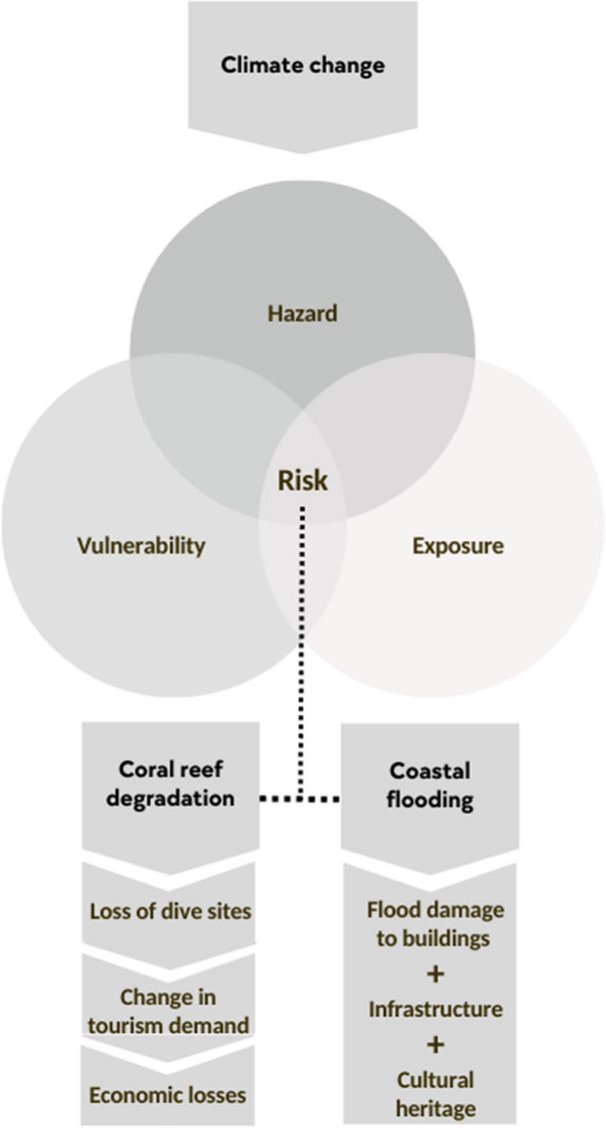

Fig. 2 Methodological framework to assess socio-economic impacts of climate change

and Surge Model (GTSM) to simulate time series of TC storm surge levels (Dullaart et al. 2021). For all other types of storms, forcing data from the ECMWF Reanalysis v5 (ERA5) global climate reanalysis was used (Hersbach et al. 2022). In the last step, tidal levels were sampled randomly and combined with surge to obtain storm tide levels; the storm tide Return Periods (RPs) were then calculated using this information.

Wave setup was simulated using significant wave heights of wind waves and swell from the ERA5 global climate reanalysis (Hawker et al. 2022). Similar to Muis et al. (2020), extreme significant wave height was obtained by calculating the RPs from the annual maxima. Based on the study by Peachey (1986), the hydrological form of a wave was simplified to the shape of a sinusoidal with the formula:

$$wave\ height = vertical\ shift + amplitude * sin((2 * \pi/period) * x - phase\ shift$$

where:

$vertical\ shift = 0\ (m)$
$amplitude = 0.71\ (m)$
$period = 10\ (s)$
$x = time\ (s)$
$phase\ shift = 2.5\ (m)$

The *DEM* used in this research is the so-called FABDEM (Hawker et al. 2022). The FABDEM is referenced to the EGM2008 geoid model (Hawker et al. 2022) and has been corrected to the reference of the WGS84 geoid model for the storm tide hydrographs (Andersen and Knudsen 2009). This DEM is chosen because it is the first global DEM to exclude forests and structures, thereby expectedly providing more accurate elevation data of the land surface.

To incorporate the dynamic component of storm tides and waves into a simulation, the reduced-physics model Super-Fast Inundation of CoastS (SFINCS) was employed (Leijnse et al. 2021). SFINCS is a dynamic inundation model, indicating the possibility of incorporating the time dimension into the simulation. In this study, the SFINCS model is preferred over the use of other studies because other modelling approaches are considered too simple as they are static (e.g., the bathtub approach), or accurate but too slow (e.g., Delft3D, XBeach).

The most important topographical input files used by the model—besides the DEM—include a bathymetry file (GEBCO_2021 Grid 2021), a land use file representing the roughness of the landscape (Buchhorn et al. 2020), and a global curve number file used for soil infiltration rates (Jaafar et al. 2019). Lastly, for the hydrography on Bonaire, the MERIT Hydro dataset was applied. This global dataset incorporates flow direction, flow accumulation, and river channel width (Yamazaki et al. 2019). The horizontal resolution of the model was set at 20 m to keep it computationally efficient for the size of the research area. The time span of the simulation was 7 days, with output calculations every 600 s for the output files. The model was adjusted to account for the constant water level of SLR prior to the storm, resulting in a more realistic future storm simulation (Leijnse 2022).

Ecological Module

The ocean near the coast of Bonaire contains coral reefs, which are a natural coastal protection against waves and storm surges (Ferrario et al. 2014). A case study from the Seychelles analysed the effects of coral reef degradation on the total wave energy that reaches the shore (Sheppard et al. 2005). Showing high variability, their model predicted that 20 years after the degradation, the wave energy reaching the shore could increase by 80% depending on the coral reef setup. In order to predict flood risks on Bonaire with deteriorated coral reefs, it was hypothesised that based on the coral reef type and profile the wave setup would also increase by 45%. This gives an indication on how coral reefs affect changes in flood risk and subsequently, the wave setup factor of 0.2 (Vousdoukas et al. 2018) was multiplied by 1.8 for use in the model's wave setup calculations, yielding a wave setup factor of 0.36. Using this new factor, the wave height was recalculated, and a coral reef deterioration scenario was simulated for the 2050 middle-of-the-road SSP2-4.5 scenario.

Exposure

Exposure Built Environment

Microsoft open-source data was used in combination with Open Street Map (OSM) data to determine the locations of all exposed assets (Microsoft Bing Maps, 2022, OSM; OpenStreetMap, 2022); other databases containing information of local buildings and addresses were not publicly available. The value of each type of structure was derived from several sources. Rider Levett Bucknall (RLB 2021) and BCQS International (2020) provide realistic construction costs for the majority of building categories. Federal Emergency Management Agency (FEMA) (2009) was consulted for the categories "schools," "government buildings," "(movie) theatres and museums," and "religious buildings" (2009). A neighbourhood sampling method was used to estimate the category of value per square metre for residential structures. Neighbourhoods were classified into four categories, and the individual value category can be found in Appendix B. For sheds, a calculation of half the price per square metre of industrial buildings was taken, since, based on fieldwork, it can be assumed that most sheds are constructed of similar materials as industrial buildings.

Similar to buildings, and following Nirandjan et al. (2022), critical infrastructure was classified into different categories: energy, transportation, drinking water, waste, health and first responders, and industry. The transportation category was considered most important, as it includes crucial international trade facilities, such as the airport and the harbour, as well as the islands' road infrastructure network.

Exposure Cultural Heritage

UNESCO defines cultural heritage as tangible monuments, artefacts, and sites that have historical, symbolic, and social values, and the intangible cultural heritage (ICH) that is embedded within this tangible cultural heritage (TCH) (Pessoa et al. 2009). Four research methodologies were used to identify and validate the most valued tangible cultural heritage assets of Bonaire: a literature study, expert interviews, participatory mapping, and social media analysis.

First, various local policy documents were reviewed in order to locate tangible cultural heritage referenced in the literature. Second, experts from culturally engaged nongovernmental organisations (NGOs) and foundations on Bonaire were interviewed to further examine how climate change is anticipated to affect tangible cultural assets on Bonaire and to validate the cultural heritage identified by the literature research. Third, a participatory mapping (PM) approach was applied; cultural experts and Bonairian residents (who had lived on Bonaire for at least two and a half years) were shown a map of the island and asked to identify cultural heritage that they thought was valuable and significant to Bonairian culture. Fourth, the findings of the literature study, participatory mapping, and expert interviews were complemented and validated by a social media analysis. In the social media analysis, 1,137 photographs that have been uploaded to Flickr by tourists and locals, were examined and categorised to identify the most frequently visited Bonairian cultural sites.

After identification of Bonaire's tangible cultural heritage, the results were mapped and subsequently merged with flood maps based on different climate projections to determine the tangible cultural heritage at risk from coastal inundation by 2050.

Exposure Economy

To assess the associated direct and indirect economic consequences of tourism losses due to climate change, an input–output (IO) modelling framework was developed. Considering the simplicity and transparency of IO models, this paper applied an IO analysis to link external ecological effects to economic impacts. The IO table of 2017 for Bonaire was constructed and updated using the supply and use table (SUT) of 2004 for Bonaire and has been structured as an industry-industry table. To estimate how the different industries have developed from 2012 to 2017, data on gross domestic product (GDP) growth and average salary growth per industry was retrieved from the Statistics Netherlands (Statistics Netherlands 2018). This results in a closed-economy IO table for the island of Bonaire for the year 2017. While an island such as Bonaire is highly dependent upon the rest of the world, there was insufficient data on international trade to explicitly incorporate it into the modelling framework.

Due to the island's small size and remoteness, its industries require high levels of imports of agricultural and manufactured products to operate. Therefore, the total intermediate demand of each industry required for production was split into domestic products (locally produced) and external products (import). Next, to better align the tourist expenditure patterns with the industry categorization of the Statistics Netherlands, the "Hospitality" sector was split up into the "Hotels" sector and the "Food services" sector. This subdivision is essential to capture the differences in expenditure profiles between stay-over tourists and cruise tourists. Since the tourism satellite account (TSA) of Bonaire (Statistics Netherlands 2012) does not account for this subdivision, the relative share of the two industries was based on the TSA of Aruba (Steenge and Van De Steeg 2010), which is assumed to have a similar structure as Bonaire. Data on tourism expenditures was retrieved from the exit survey of Schep et al. (2013) and the 2017 Tourist Exit Survey'' of STMP Bonaire (Croes et al. 2019). Finally, the total tourism expenditures per category are matched with its related industry in the IO table. The economic structure of Bonaire for the current situation and for the year 2050 was predicted by updating the developed IO matrix of 2017 using a CRAS (cell-corrected RAS-algorithm) approach, as proposed by Lenzen et al. (2009). CRAS is capable of compromising between inconsistent matrix entries, which is appropriate given that the 'new' set of constraints for 2050 is derived by making assumptions regarding sectoral and GDP growth for 2050. More information about the application of the CRAS approach in this study is presented in Appendix C.

Moreover, we apply the concept of "social carrying capacity" to predict changes in dive tourism arrivals. This concept captures the restricting factor of the availability of healthy reefs when visiting a diving destination (Davis and Tisdell 1995). The social carrying capacity of the coral reef on Bonaire is calculated by multiplying the number of quality dive spots by the maximum number of divers that can be sustained at each dive site (Koks and Van Zanten 2015). By comparing the total number of dives that the island can "supply", with the total "demand" for dives by visitors, a "resource balance" is established that indicates whether the island is able to accommodate the expected number of dive tourists. The resource balance in 2017 amounted to a surplus of 629,000 dives, indicating that the current demand for dives is within the social carrying capacity of the island. It is assumed that the total number of dives cannot exceed the social carrying capacity.

Vulnerability

Vulnerability Dive Sites and Tourism Demand

To evaluate the decreasing supply of dives for tourists, the degradation and quality of local coral reefs were used to simulate vulnerability of dive sites. First, to estimate the effects of climate change on the quality of coral reefs around Bonaire, the Reef Health Index (RHI) (Kramer et al. 2015) was utilised as an indicator of coral reef quality that could be modelled under climate change scenarios. This index was developed to assess the state of the Mesoamerican Reef in the Caribbean (Díaz-Pérez 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). 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).

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 and Van Zanten (2015), a macroeconomic IO model with an ecological module. Key reef health indicators are impacted by global climate stressors through the external effects of algal blooms, ocean acidification, and coral bleaching. The magnitude of these global stressors depends on the CO2eq 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.

Vulnerability Built Environment

This part of the study aims to identify the extent to which Bonaire's buildings and critical infrastructure will be directly impacted by future climate change in 2050, focusing on floods and storms specifically. To identify the vulnerability per asset, a classification was made based on building height. The buildings were classified using the earlier described neighbourhood sampling, as no detailed data was available. A vulnerability curve was 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, the road network's connectivity was evaluated. 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. To determine which roads are cut-off and, hence, unusable, a line polygon connectivity checking tool in a GIS was utilised. By combining the damages to both buildings and critical infrastructure, a more complete overview of the expected direct impacts is presented (Garschagen et al. 2016).

Vulnerability Economy

One of the key strengths of IO analysis is to identify how changes in one sector may influence changes in another sector through inter-industry linkages. These linkages allow us to determine the economy-wide impacts of environmental shocks from tourism losses to other industries in the economy of Bonaire. This concept is also known as the 'multiplier effect': the variances in output of other industries within an economy when the demand of a single industry changes. The magnitude of these interrelationships is estimated by determining the multiplier coefficients. The multiplier effects of tourism were estimated using the approach of Frechtling and Horváth (1999). The process of estimating total revenue losses was based on the number of stay-over and cruise tourist arrivals, the average number of nights spent on Bonaire, and the average tourist expenditures per tourist per day (Mayer and Vogt 2016), as shown in Appendix D. By coupling tourist expenditure with our macroeconomic framework, we can assess the macroeconomic impact of tourism losses. We define these losses as the changes in the GDP of Bonaire due to the induced effects of tourism demand.

Results

Impacts on the Built Environment and Cultural Heritage due to Coastal Inundation

Coastal Inundation

Figure 3 illustrates the inundated areas of Bonaire in 2050 under the climate projections SSP1-2.6, SSP2-4.5 and SSP5-8.5. It is noticeable that mainly the parts in the South of Bonaire are predicted to be inundated by 2050 under all climate scenarios and that differences in predicted inundation levels between climate scenarios appear to be minimal. This latter insight can be explained by the minor variations in SLR.

To indicate the difference in inundation across the SSP scenarios, the total inundated surface area is calculated and presented in Fig. 4 and shows that the total inundated surface area is between 8.0 and 8.3 km^2. The saliñas and mangroves are excluded from the total inundated surface area because these areas are already inundated. However, it must be noted that the characteristics and, hence, the services provided by these ecosystems may change due to permanent inundation and coastal flooding.

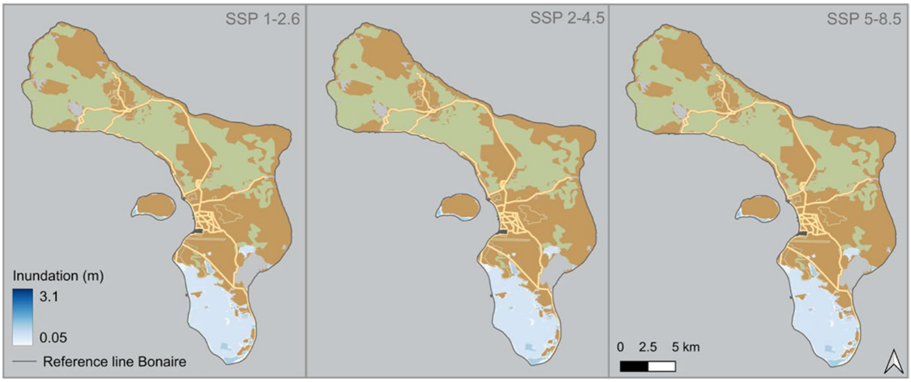

Fig. 3 Inundation maps of Bonaire—climate scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5 in 2050

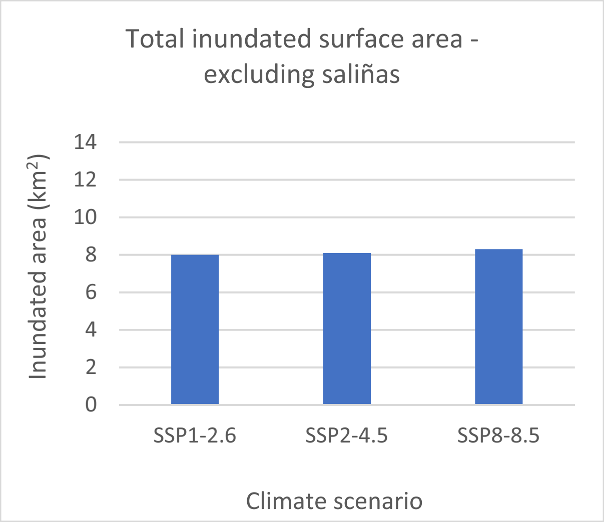

Fig. 4 Histogram of the total inundated surface area—climate scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5 in 2050. The saliñas and mangroves are excluded from the total inundated surface area

Figure 5 illustrates the projected inundation difference between a healthy and completely degraded coral reef for the SSP2-4.5 scenario in 2050. Assuming that reef degradation increases WSU by 45%, the flood extent increases. The total inundated surface area, excluding the saliñas, increases by 41%, from 8.0 to 11.3 km^2. Inundation depth increases by an average of approximately 0.24 m, with a larger increase directly on the coastline.

Impact and Damage to Buildings

As presented in Table 1, the differences in monetary impacts of flood hazards across the various climate scenarios for 2050 are relatively small: expected damage values associated with climate scenario SSP 5–8.5 are estimated to be almost 3,6% higher than the expected costs related to climate scenario SSP 1–2.6. This is due to the fact that the flood risk does not affect additional buildings in the most extreme climate scenario compared to the least extreme climate scenario. However, although the number of buildings hit remains the same in the different climate projections, namely 54, the damage costs are expected to increase due to higher levels of inundation, which can cause additional damage to the houses hit. The difference in total damage between SSP 1–2.6 and SSP 5–8.5 is approximately 500,000 USD.

Figure 6 indicates that in the SSP 1–2.6 scenario for the year 2050, 38 of the 54 buildings exposed to storm inundation are located in the neighbourhood of Belnem, which is significantly more compared to the other neighbourhoods, resulting in 3.58 USDm of the total damage of 13.8 USDm. The estimation that (at least) 38 out of the 876 (4.3%) buildings in Belnem will be hit in 2050, 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.

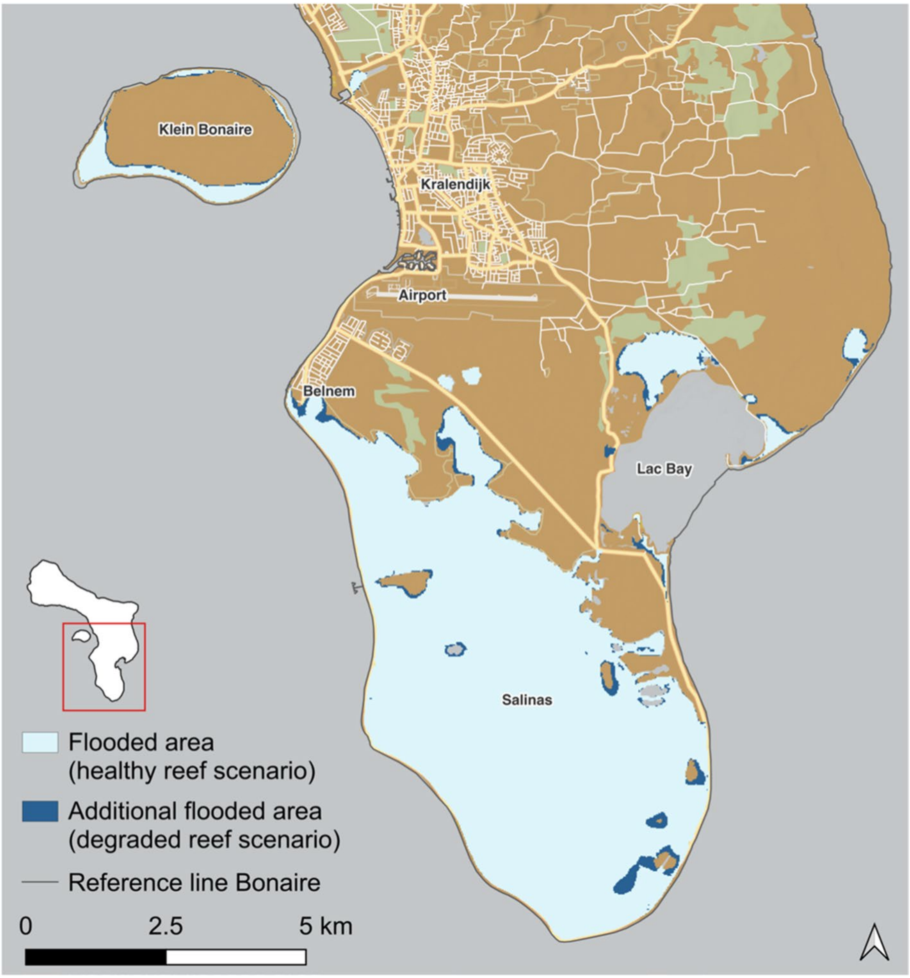

Fig. 5 Inundation map that illustrates the flood extent for 2050 under a healthy reef scenario and a degraded reef scenario—climate scenario SSP2-4.5

Impacts on Roads and Critical Infrastructure

Figure 7 illustrates Bonaire's key infrastructure, such as essential buildings and roadways, in 2050 under two climate projections (SSP 1–2.6 and SSP 5–8.5). All of Bonaire's essential infrastructure that is vulnerable to climate-driven flood risks is located in the South and/or along the coast.

Table 1 Overview of the effects of climate scenarios SSP 1–2.6, SSP 2–4.5 and SSP 5–8.5 in 2050

Scenario	Year	Number of buildings hit (#)	Average inundation of affected buildings (m)	Total damage (USDm)
SSP1-2.6	2050	54	0.345	13.8
SSP2-4.5	2050	54	0.360	14.1
SSP5-8.5	2050	54	0.361	14.3

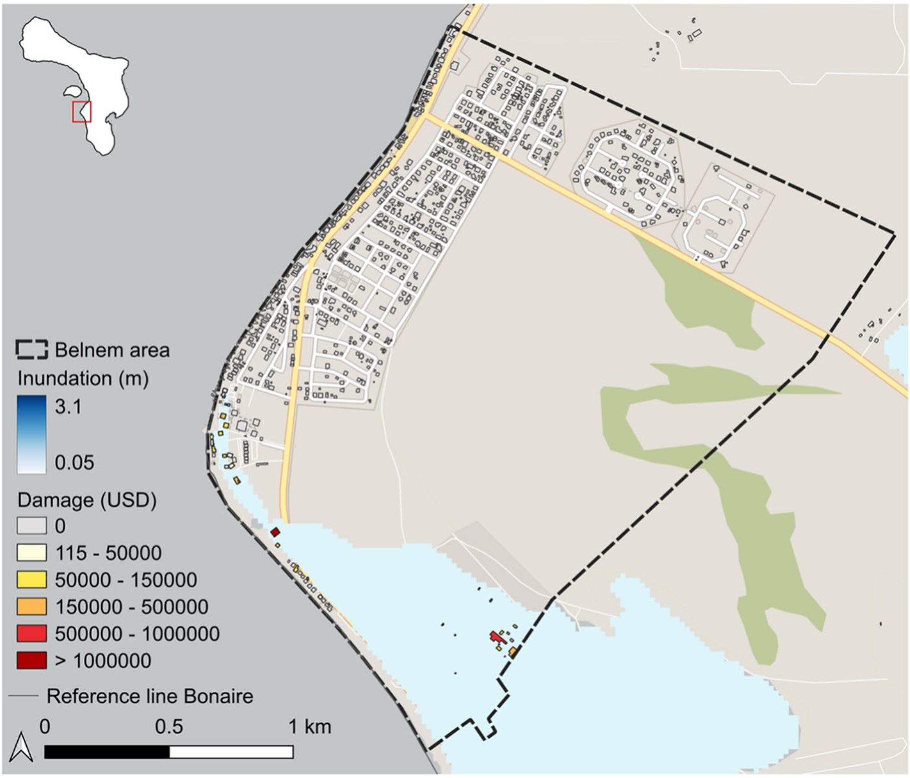

Fig. 6 Building damage in Belnem—climate scenario SSP 1–2.6 in 2050

Local firefighters stated that 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 (Fire fighter, personal communication, May, 2022). When considering the impact on infrastructure such as roadways, even roads that are not immediately exposed to flood threats can be severed from the network, rendering the entire road inoperable. As shown in Fig. 7, all roads in the southern part of Bonaire will be unusable in 2050 under climate scenarios SSP 1–2.6 and SSP 5–8.5. Therefore, emergency services cannot reach the Cargill facilities and other buildings in these areas of Bonaire. In addition, the roads leading to the salt ponds are reported as impassable, posing a severe threat to Cargill's operations. Moreover, the inundation depth of salt ponds might fluctuate following a coastal flooding event, and it is unknown how this affects the services provided by the ecosystems, such as salt provision.

Impacts on Tangible Cultural Heritage

Figure 8 presents the cultural heritage that has been identified by literature, cultural experts, Bonairian residents, and/or the social media analysis.

As shown in Fig. 8, some locations have been identified in all three analyses, while others have only been identified by one of the applied research methods. For example, the literature review identified multiple locations around Rincon (e.g., 10, 12, 13, & 14 on the map) and

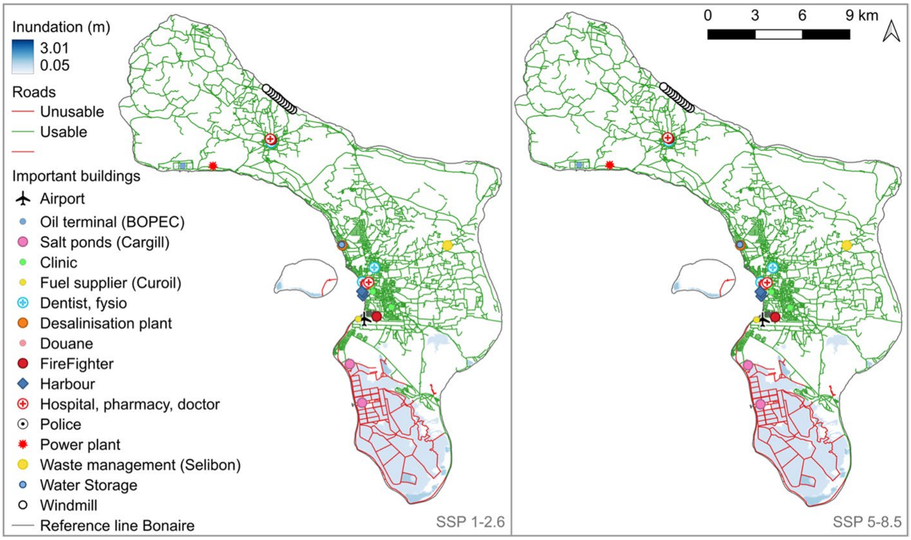

Fig. 7 Impact on critical infrastructure on Bonaire—climate scenarios SSP 1–2.6 and SSP 5–8.5 in 2050

traditional buildings in Kralendijk (e.g., 21, 22, & 23), while these were not mentioned during the fieldwork. The participatory mapping, on the other hand, 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 ponds, the slave huts, Willemstoren, and Lac Bay, thereby validating the literature review and fieldwork results.

The majority of Bonaire's tangible cultural heritage is located in coastal, mostly low-lying areas and is vulnerable to inundation from SLR and storm surges. As shown in Fig. 9, besides the Gotomeer, in 2050 no identified tangible cultural heritage in the North is identified as vulnerable to permanent or storm flooding, but almost all identified tangible cultural heritage in the South is considered susceptible already under climate scenario SSP 1–2.6, including the white and red slave huts, Flamingo sanctuary, Willemstoren, and old salt pans.

The Social Carrying Capacity of Dive Sites

Expected Changes in 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 and the social carrying capacity of these dive sites to accommodate dive tourism. Table 2 presents an overview of the change in coral reef quality and the expected diving demand and supply of quality dive sites in 2050 under each IPCC AR6 scenario. It is estimated that Scenario SSP1-2.6 shows a positive resource balance, since the coral reefs are expected to have the capacity to carry all diver demand. However, SSP2-4.5 displays a deficit of 174 thousand dives 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, over 17 thousand dive tourists cannot be accommodated on Bonaire's coral reefs in 2050 under scenario SSP2-4.5. This deficit progressively increases in scenario SSP5-8.5

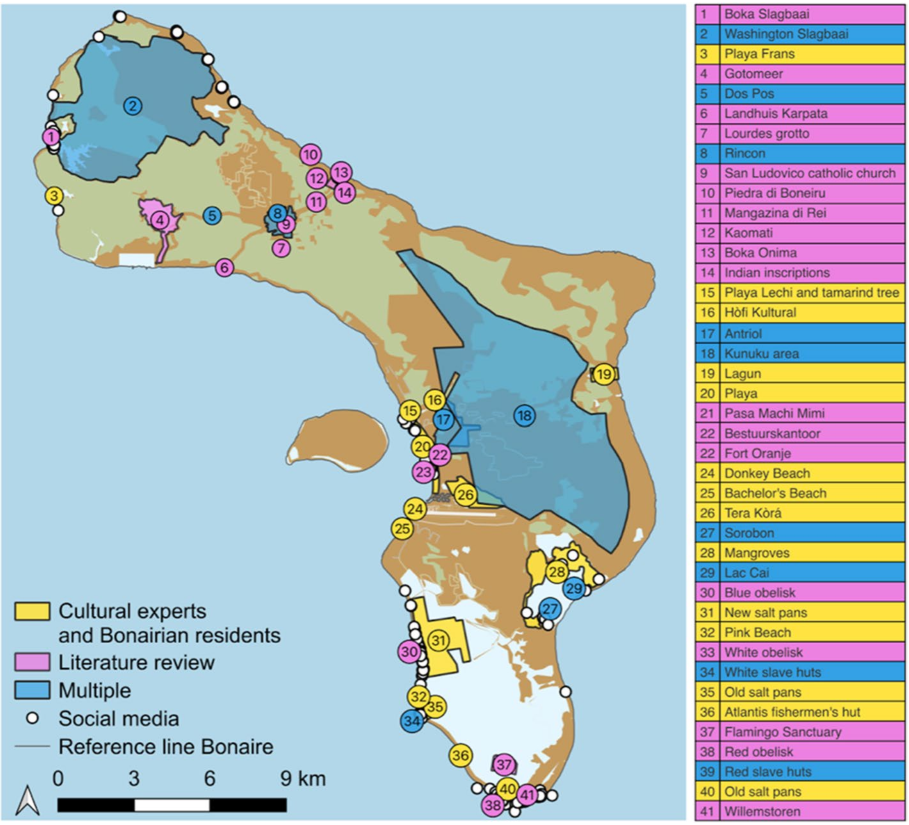

Fig. 8 Map comparing the cultural heritage identified during the literature review, by the cultural experts and Bonairian residents, and social media analysis

(117.6 thousand dive tourists). If it is assumed that the dive tourists that cannot be accommodated on Bonaire's coral reefs will not visit the island, this would have an effect on the tourism expenditures and thus on total tourism demand, as shown in Table 2. While in SSP1-2.6 no change in tourism demand is expected, a reduction of over 205 USDm is expected in SSP5-8.5.

Changes in Economic Output Per Sector

Table 3 summarises the macroeconomic effects of a change in tourism demand as a result of 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 SSP 1–2.6 does not result in any decline in tourism demand. Hence, no indirect economic consequences of reef degradation are found. In scenario SSP 2–4.5, the decline of 30.3 USDm in final tourism expenditures is divided among the relevant industries according to the related expenditure categories. Subsequently, this study finds that GDP is expected to shrink by 25.7 USDm. Considering "high growth", "business-as-usual", and "low growth" scenarios for GDP development, Bonaire is expected to potentially experience an economic contraction of 2.4%, 2.7%, and 3.8%, respectively. As

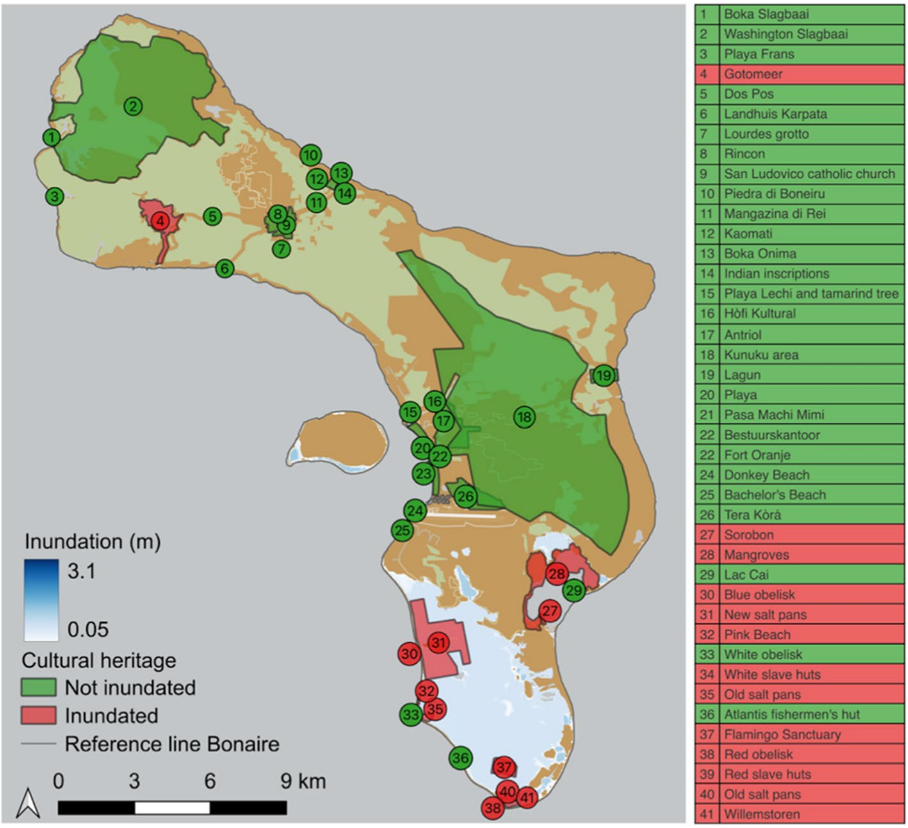

Fig. 9 Cultural heritage identified on Bonaire overlaid with the inundation map for the SSP 1–2.6 scenario in 2050

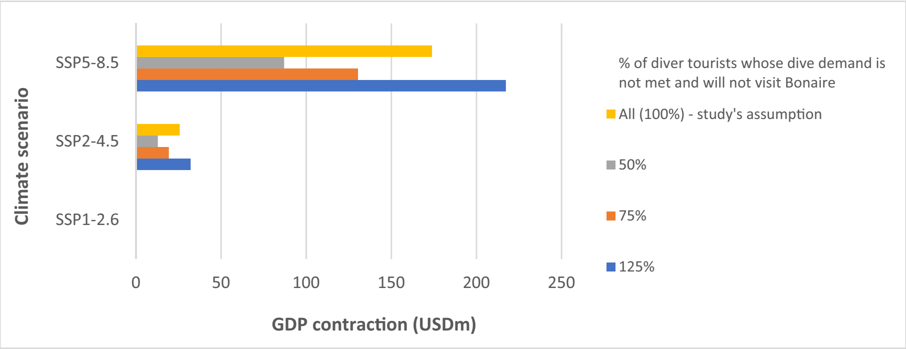

Fig. 10 Bar chart presenting the results of a sensitivity analysis on the effects of different tourism responses to coral reef deterioration on Bonaire's GDP

Table 2 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)	SSP1-2.6	SSP2-4.5	SSP5-8.5
Quality dive sites (#)	89	86 (-3%)	72 (-19%)	13 (-85%)
Average RHI score	2.9	3 (10%)	2 (-22%)	1 (-49%)
Social carrying capacity (# dives)	1,515,967	1,464,867 (-3%)	1,220,722 (-19%)	218,455 (-86%)
Demand for dives (# dives)	868,014	1,394,365 (61%)	1,394,365 (61%)	1,394,365 (61%)
Resource balance (# dives)	647,953	70,501	- 173,643	- 1,117,592
Surplus/deficit of diver demand (# dive tourists)	64,795	7,050	-17,364	-117,592
Changes in final tourism demand (USD; 2017 prices)	0	0	-$30.27 mln	-$205.02 mln

expected, SSP5-8.5 shows the most severe indirect economic losses. Total indirect economic losses amount to 173.9 USDm, or an economic contraction of between -16.3% and -25.4%, depending on the economic growth scenario. The tourism sectors such as “Hotels”, “Food services”, and “Other real estate activities” are impacted most in each scenario. For instance, in scenario SSP 5–8.5, the added value of the “Hotels” sector is expected to decrease with 28.7% compared to the baseline (Table 3). 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.

Sensitivity Analysis on Annual Tourism Demand

The data in Table 2 are based on the assumption that all scuba divers whose demand for diving cannot be met due to degraded dive sites will not visit the island. This assumption is founded on the fact that Bonaire is often referred to as "diver’s paradise" and the majority of tourists visit the island for diving (Tourism Corporation Bonaire 2008; Wolfs et al. 2015). In addition, Sookram (2009) states that reef deterioration in the Caribbean has a substantial impact on the number of tourist arrivals, confirming the strong dependence of tourism revenues on the quality of dive sites. However, a multitude of other factors influence tourism demand, such as altering policies, the availability of other tourist attractions and activities on Bonaire and alternative holiday destinations, and the island’s reputation, among various other factors. To test the impact of this assumption, we conducted a sensitivity analysis with three alternative potential tourism demand effects on coral reef degradation and associated GDP implications: 50%, 75%, and 125% of the dive tourists who cannot be accommodated on Bonaire’s coral reefs will not visit the island (see Fig. 10). As expected, although the changes in GDP contractions under climate scenario SSP 2–4.5 are modest—ranging from 13 to 32 USDm depending on low to high tourism demand responses on degraded coral reefs—the difference under climate scenario SSP 8–5.8 is substantial and accounts for 130 USDm—contractions in GDP range from 87 to 217 USDm, depending on the effects on tourism demand (see Appendix E for more detailed results).

Discussion

The projections show that, similar to various other (Caribbean) islands (Carabine and Dupar 2014; Macpherson and Akpinar-Elci 2013; Robinson 2018; Scandurra et al. 2018), Bonaire will face several severe risks and disruptions under climate change. By 2050, even under climate projection SSP 1–2.6, which corresponds with a temperature increase of less than 2 degrees by the end of this century, as agreed in the Paris climate agreement, critical assets such as buildings, roads, and tangible cultural heritage are at risk of coastal inundation. Zellentin (2015) states that the citizens of SIDS will not only lose their physical homeland but also their social structure and cultural community due to anthropogenic climate change. Our study finds that various cultural assets, such as the slave huts, on Bonaire are at risk. The expected loss of this cultural heritage may have severe impacts on society, as it may lead to a decline in cultural identity and social cohesion. As opposed to findings presented in studies on other Caribbean islands (e.g., Monioudi et al. 2018; Wang 2020), Bonaire’s international transportation airport and seaport, which

Table 3 GDP losses under climate scenarios considering low (LG) and high (HG) GDP growth scenarios. Losses are listed per sector as a percentage loss in value added compared to the expected GDP in 2050

Sector	Baseline		SSP2-4.5			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
Agriculture, Fishing, Mining	15.07	23.49	0.02	0.1%	0.1%	0.11	0.7%	0.5%
Manufacturing	13.16	20.50	0.43	3.3%	2.1%	2.94	22.3%	14.3%
Electricity, gas and water supply	33.88	52.78	1.13	3.3%	2.1%	7.63	22.5%	14.5%
Construction	49.20	76.64	0.32	0.6%	0.4%	2.16	4.4%	2.8%
Trade	88.76	138.28	3.15	3.6%	2.3%	21.36	24.1%	15.4%
Hotels	36.41	56.72	1.56	4.3%	2.7%	10.55	28.7%	18.6%
Food services	31.91	49.71	3.27	10.3%	6.6%	22.15	69.4%	44.6%
Transport, information and communication	53.42	83.23	2.91	5.5%	3.5%	19.73	36.9%	23.7%
Financial intermediation	36.72	55.65	1.52	4.3%	2.7%	10.29	28.8%	18.5%
Other real estate activities	73.63	114.71	5.98	8.1%	5.2%	40.47	55.0%	35.3%
Public administration and defence	77.55	120.82	0.66	0.8%	0.5%	4.46	5.8%	3.7%
Education	39.74	61.91	0.17	0.4%	0.3%	1.13	2.8%	1.8%
Health	69.22	107.83	1.02	1.5%	0.9%	6.89	10.0%	6.4%
Other services	38.57	60.10	3.54	9.2%	5.9%	23.96	62.2%	39.9%
Total	656.2	1,022.4	25.7	3.9%	2.5%	173.9	26.5%	17.0%

provide critical access for all external trade and tourism, are not considered at risk by 2050. However, climate change is predicted to have a significant impact on various other essential buildings and infrastructure by 2050, as well as 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).

Similar to a study by Monioudi et al. (2018), it was found that SLR is the largest contributor to coastal inundation. While the expected differences in SLR between the selected climate scenarios are minimal, the differences in inundation, and consequently the accompanying negative effects, will be much more evident later in the century since the SLR variances between the various climate scenarios are much greater (IPCC 2021). Although coral reef degradation and coastal inundation are dependent on the selection of wave setup and loss of energy, the inundation results show that sensitivity is low.

The overall reef health index declines under climate scenarios SSP2-4.5 and SSP5-8.5 by 2050. Although these results are in line with previously published studies stating that climate change threatens coral reefs (Hoegh-Guldberg and Bruno 2010; Hoegh-Guldberg et al. 2017; Pandolfi et al. 2011; Crabbe 2008), it must be noted that the coral reef's health is expected to remain stable under SSP1-2.6 by 2050, indicating the importance of (global) climate change mitigation efforts. This loss of coral reefs will not only further amplify storm inundation and thus lead to an increase in the inundated areas and inundation depth, but in the most pessimistic scenario, Bonaire could also experience an economic contraction of 25%, which would have significant socio-economic implications for the island's inhabitants. However, the predicted economic contraction is considered susceptible to various factors, including the selected climate scenario and the assumed tourism responses to coral reef degradation, among others.

Nevertheless, it is evident that in the absence of timely planning and implementation of adaptation measures, the impacts of climate change may have serious implications for inhabitants' lifestyles and wellbeing. This study can serve as a foundation for stakeholders to develop and implement effective responses. We strongly recommend that further steps 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 local authorities should implement coastal adaptation measures to protect at-risk communities and tangible cultural heritage from coastal flooding hazards. In addition, we recommend that future research concentrate on other ecological climate change-induced alterations, such as erosion and drought, as well as appropriate adaptation strategies against those changes.

While our study provides a holistic and unique view of the effects and impacts of climate change on a small Caribbean island, this study has limitations that are typical for modelling environmental, economic, and social interrelationships and integrated climate assessments. To start, although research on anthropogenic climate change is now well established (IPCC 2021), climate change modelling comes with various uncertainties. Ultimately, any model that uses numerical modelling comes with different sources of uncertainty (Foley 2010). Since climate systems and the models used 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. Consequently, uncertainties are inherent to these integrated modelling methods, and additional future sensitivity assessments will be necessary to determine how this may impact the conclusions of this study.

Furthermore, as is common for most small islands (Van Beukering et al. 2007), the absence of certain types of (high-quality) data is a limitation that contributed to the levels of uncertainty in all the components of the study. For example, in the current study, modelled storm tracks were applied due to a lack of historical data. Moreover, the FABDEM dataset, based on satellite data, applied in this study has a spatial resolution of 30 m. Accurate elevation data are crucial inputs for geosciences and other disciplines (Hawker et al. 2022). For example, Vousdoukas et al. (2018) showed that a change in resolution from 10 to 100 m could change the estimated expected annual damages by 200%. A lack of data affects the IO model as well, since Bonaire fundamentally lacks publicly 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. Diverse and up to date datasets can be vital to further strengthening the predictive power of the ecological module and the IO model that was developed in this study. Moreover, assumptions had to be made concerning tourism responses to changing (quality of) diving sites, which appeared to have significant implications for projected GDP contractions.

It is furthermore important to acknowledge that the study utilised a closed-economy IO table for Bonaire, although the island's economy is open in practise. Data scarcity also prevented the development of an open-economy IO modelling framework, which implies that certain trends with diverse effects on Bonaire's economy could not be included in the model. For instance, the development of the tourism industry on Bonaire is dependent on trends in international tourism demand. On the one hand, factors such as population growth and income growth could lead to an increase in international tourism demand. In theory, an increase in international demand would, in an open economy, mitigate the anticipated GDP contraction in our results. On the other hand, altered climate change policies may increase future cruise- and/or airfare prices, which may reduce demand for tourism destinations that can solely be reached through air or sea transportation. Such policies are anticipated to exacerbate the predicted GDP contraction on Bonaire. In addition, when considering an open economy, the attractiveness of competing tourist destinations should also be considered, since the effect of a change in coral reef quality on the number of dive visitors also depends on supply of quality dive sites in competitive tourism destinations. As dive sites in other destinations are also expected to degrade, Bonaire's competitive advantage as a dive destination may not be affected. However, there's also a possibility that a global decline in coral reef quality will have a negative impact on the global demand for dive tourism and, consequently, also on tourism demand on Bonaire. Overall, it is anticipated that the various influences of an open economy framework will have an effect on tourism demand and related economic growth, but it remains uncertain how the trends will manifest in practise.

The various information gaps necessitated improvisation in obtaining credible evidence by employing alternate data collection techniques. Such methods included participatory mapping to identify 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 employ similar innovative data collection methods and assumption approaches to fill data and knowledge gaps.

Conclusions

This study aimed to explore the socio-economic impacts of climate change on Bonaire. First, we analysed the biophysical effects of climate change under different climate scenarios in 2050, namely coral reef degradation and inundation. This information was subsequently applied to determine socio-economic impacts associated with climate change, such as damage to the built environment and tangible cultural heritage, as well as to economic development as a consequence of a reduction in tourism. These impacts have all been studied in previous literature and were found to be impacted by climate change. However, this is the first study that analyses all of the aforementioned components in one research endeavour to create a more holistic picture of the impacts of global warming.

On Bonaire, coastal inundation is predicted to damage the built environment, infrastructure, and tangible cultural heritage. Moreover, the degradation of coral reefs will not only exacerbate storm flooding but will also have detrimental effects on Bonaire's economic growth. 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, recognizing geographical and cultural diversity, it is recommended that other low-lying SIDS also evaluate the impacts, vulnerabilities, and adaptation options against climate change hazards through primary research. The type and variation of research methods employed in this research could serve as a basis or inspiration for various other data scarce islands threatened by the effects of climate change.

Our results suggest that direct action is needed to protect the island of Bonaire and its inhabitants against the implications of climate change. In the absence of timely planning and implementation of adaptation measures, the impacts of climate change may have serious implications for inhabitants' lifestyle and wellbeing. Based on these results, it is evident that further research on potential adaptation measures, as well as immediate action to develop and implement these types of measures, are urgently needed.

Appendix A Elaboration on the Most important Consulted Datasets and Applied Models

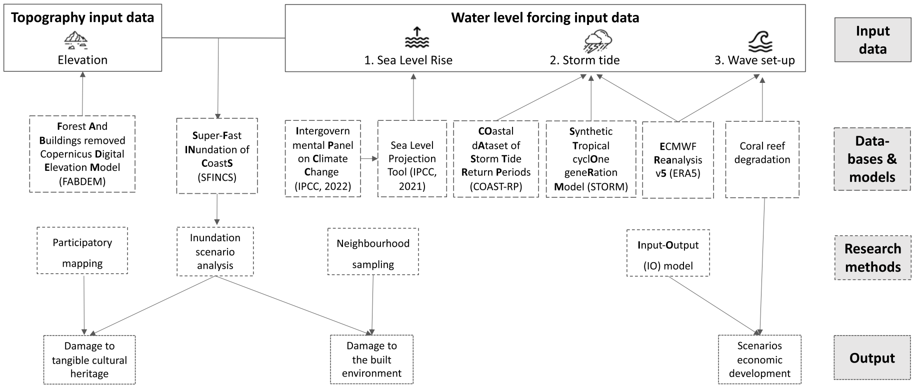

Fig. 11 Research framework presenting the most important consulted datasets, applied models, and research methods and anticipated outputs. Databases were selected based on open access and highest resolution/accuracy

Table 4 Description of consulted datasets and applied models

Full title	Working title	Source	Description
Datasets			
Intergovernmental Panel on Climate Change	IPCC	IPCC 2022	The IPCC prepares comprehensive Assessment Reports about knowledge on climate change, its causes, potential impacts, and response options. In this study, different climate projections are taken from this report
COastal dAtaset of Storm Tide Return Periods	COAST-RP	Dullaart et al. 2021	This is a global dataset with storm tide levels corresponding to ten different return periods, ranging from 1 up to 1000 years
International Best Track Archive for Climate Stewardship	IBTrACS	Knapp et al. 2010	This dataset provides global tropical cyclone best track data in a centralised location to aid our understanding of the distribution, frequency, and intensity of tropical cyclones worldwide
MERIT Hydro	N.A	Yamazaki et al. 2019	This is a global hydrography dataset that incorporates flow direction, flow accumulation, and river channel width
ECMWF Reanalysis v5	ERA5	Copernicus Climate Change Service (C3S)	ERA5 provides hourly estimates of a large number of atmospheric, land, and oceanic climate variables. It combines vast amounts of historical observations into global estimates using advanced modelling and data assimilation systems
Models			
Synthetic Tropical cyclOne geneRation Model	STORM	Bloemendaal et al. 2020	This model integrates meteorological data with the publicly available ERA5 dataset (ECMWF) to adjust for sea surface temperature and atmospheric pressure. It can extract and amplify data about tropical cyclones from any meteorological dataset to provide information about their possible tracks and intensities

Table 4 (continued)

Full title	Working title	Source	Description
NASA IPCC AR6 Sea level projection tool	N.A	IPCC 2021	The NASA Sea Level Projection Tool allows users to visualise and download the sea level projection data from the IPCC 6th Assessment Report (AR6)
Super-Fast Inundation of CoastS	SFINCS	Leijnse et al. 2021	SFINCS is a dynamic inundation model, indicating the possibility of incorporating the time dimension into the simulation
Forest And Buildings removed Copernicus Digital Elevation Model	FABDEM	Hawker et al. 2022	A DEM is the digital representation of the land surface elevation relative to a chosen reference point. This is the first global DEM with forests and buildings removed from the Copernicus GLO 30 DEM
Input–Output model	IO model	Leontief 1951	An IO model can generally be regarded as a static demand-driven model that assumes a linear, time-invariant, fixed-proportions output function for all economic agents. A key strength of the analysis is the application of Leontief multipliers, which show the interdependencies between the output of industries within an economy in case of a sudden shock

Appendix B Classification and Values of Buildings on Bonaire

Table 5 Building classification and value per square meter categories for 2050

System	Subsystem	Includes	Source	Year	Value in 2050 (in m^2)
Health and first responders	Healthcare	Clinic, doctor, dentist, pharmacy	BCQS	2020	$ 5,074
		Hospital	FEMA, Hazus	2020	$ 6,688
	Firefighters	Fire station	FEMA, Hazus	2016	$ 4,659
	Police	Police station, prison	FEMA, Hazus	2016	$ 4,659
	General services	Town hall (small), government offices	FEMA, Hazus	2016	$ 2,740
Education	Education	School, kindergarten, library	RLB	2021	$ 3,465
Commercial	Shops and retail	Retail trade, dept store	RLB	2021	$ 2,701
		Wholesale trade, warehouse medium	RLB	2021	$ 2,860
	Offices	Personnel and repair services, garage	RLB	2021	$ 1,827
		Prof/tech. business services, office medium	RLB	2021	$ 2,065
		Banks	RLB	2021	$ 4,687
	Hospitality	Entertainment and recreation, restaurants	BCQS	2020	$ 5,074
		Threatre, cinema, musea	FEMA, Hazus	2016	$ 3,347
		Hotel 5 star	RLB	2021	$ 5,163
		Hotel 3 star	RLB	2021	$ 1,772
	Industry	Industry	RLB	2021	$ 1,827
	Religious buildings	Church, other religious buildings	FEMA, Hazus	2016	$ 3,574
Residential	Residential	Modest	BCQS	2020	$ 1,772
		Medium	BCQS	2020	$ 2,336
		High	BCQS	2020	$ 3,625
		High +	BCQS	2020	$ 4,027
		Shed	RLB, half of industry	2021	$ 913

Appendix C Elaboration on the CRAS Approach

The economic structure of Bonaire in 2050 is predicted by updating the developed IO matrix of 2017 using a CRAS approach, as proposed by Lenzen et al. (2009). The CRAS-algorithm (cell-corrected RAS-algorithm) is an adoption of the original RAS-algorithm that was developed to update IO tables by Stone (1961). In his method, an old matrix A, with row sum $_i$ and column sum $_i$ is transformed to a 'new' matrix Y that satisfies a 'new' set of given row sums and column sums with minimum loss of information (Stone 1961). However, the original RAS method only works when the start matrix A solely has non-negative entries (Bacharach 1970). Hence, Junius and Oosterhaven (2003) developed a general mathematical device that can be applied to original matrices with both negative and positive entries, which was later corrected by Lenzen et al. (2009) for additional issues, for example, when handling zeros as initial entries. In addition, CRAS is also able to compromise between inconsistent matrix entries. This is especially helpful since the 'new' set of constraints for 2050 are obtained by making assumptions on sectoral and GDP growth for 2050. Three economic scenarios are developed for Bonaire: a (1) high growth scenario, a (2) business-as-usual (BAU) scenario, and a (3) low growth scenario. Again, the economic scenarios start in the base year 2017 and run until 2050. The GDP growth rates in every scenario are corrected for inflation to translate the economic impact of reef degradation on output to 2017 prices. The problem that needs to be resolved is to find a 'new' matrix Y that deviates least from the original matrix A, given the set of new row and column constraints, row vector $_n$ and column vector $_n$. The matrix entries should be chosen in order to satisfy the following target function (Wiedmann et al. 2007):

$$t'^{(A,Y)} = arg\ arg \sum_i \sum_j \left| z_{i,j} \right| \ln \frac{z_{i,j}}{e} \quad \text{With } z_{i,j} = \frac{x_{i,j}}{a_{i,j}} \tag{1}$$

$$\text{s.t.} \forall i = \sum_j x_{i,j} = X_n,\ \forall j = \sum_j x_{i,j} = Z_n \tag{2}$$

where target function t' is minimized, given the constraints that the sums of all sector outputs $x_{i,j}$ are equal to the column and row totals of the IO matrix.

Appendix D Elaboration on the Process of Estimating Total Revenue Losses

First, the annual number of visitors to Bonaire was proxied using the resource balance. This paper assumes that divers will not visit the island if their dive demand cannot be met. In the case of a deficit in the resource balance, the demand for dives exceeds the supply. Consequently, not all divers that are willing to visit Bonaire can be facilitated. Assuming that every diver demands ten dives per stay (Council Underwater Resort Operators, personal communication, May 2022), the number of divers that will not visit Bonaire could be calculated. For instance, when the resource balance equals -100 thousand dives in 2050, the demand of 10 thousand divers cannot be satisfied. Therefore, total tourism arrivals decline by 10 thousand on the island. However, the type of tourist arrivals should also be differentiated since stay-over tourists and cruise tourists have different expenditure patterns.

According to Mercera, CEO of the Tourism Corporation Bonaire (TCB), Bonaire is planning to limit stay-over arrivals to a maximum of 250 thousand a year to prevent mass tourism on the island and to remain a unique destination (Nederhof 2022). Assuming a similar growth rate of stay-over-arrivals as in the period of 2001 until 2019, it is expected that Bonaire will have reached the maximum amount of 250 thousand stay-over tourists by 2029. Simultaneously, cruise tourism is expected to be restricted to focus more on high-end tourism (Croes et al. 2019). Cruise ships will most likely be limited to one ship a day, as suggested by Nederhof (2022). Since cruise ships generally only visit Bonaire between October and April, and assuming an average capacity per ship of 1224 passengers (Wolfs et al. 2015), this paper predicts a maximum of 259.5 thousand cruise tourist arrivals by 2050. As mentioned in Sect. 3.3, it is assumed that 51.26% of total stay-over tourists and 4.35% of cruise tourists are divers. Employing these rates to the preceding example of a shortage of 10 thousand divers, we would find a decline of 9.2 thousand stay-over tourists arrivals and 0.8 thousand cruise tourist arrivals.

The decline in stay-over and cruise tourist arrivals affects the IO table through the final tourism demand. In turn, final tourism demand is based on the average tourist spending, "the total consumption expenditure made by a visitor on behalf of a visitor for and during his/her trip and stay at destination" (UN 1994, p. 21). A decline in X amount of stay-over tourists on Bonaire would result in total tourist expenditures that are lowered by X multiplied by the average expenditures of a stay-over tourist (i.e.1,886 USD per stay). Similarly, a decline in Y amount of cruise tourists would result in a final demand that is lowered by Y multiplied by the average added value of a cruise tourist (i.e., 122.13 USD per stay). The tourism revenue loss per category 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 needs to be constructed. This matrix provides the technical coefficients necessary to estimate changes in intermediate demand between industries when the final demand changes. Subsequently, the sum of all aggregated changes in intermediate demand reflects the level of changes in the total output of Bonaire. The last step to finding the total macroeconomic impact of reef degradation is to estimate changes in the GDP of Bonaire by 2050.

$$GDP = GVA + TP - SP \tag{3}$$

where GDP is the gross domestic product, GVA denotes the aggregated gross value added of all industries in Bonaire, TP describes the taxes on products, and SP defines the subsidies on products. Similar to the changes in intermediate demand, the changes in GVA, TP, and SP are estimated using the Leontief matrix. The coefficients of a sector's GVA (CVAi) are obtained by dividing the value added per sector (VAi) by the total output of the sector (Xi) (Furtuoso and Guilhoto 2000). Subsequently, the CVAi are multiplied by the Leontief matrix (I – A)-1 to obtain the technical coefficients TVAi. Since total output Xi decreases when the total intermediate demand decreases, changes in the GVA can be calculated by taking the sum of TVAi multiplied by the changes in total output Xi of each sector. Hence, Eq. (4) can be developed.

$$\Delta GVA_{Bonaire} = \sum_i \left(TVA_i * \Delta X_i\right) \tag{4}$$

Likewise, changes in TP and SP are determined by calculating the corresponding technical coefficients TTPi and TSPi and multiplying them by the change in total output Xi of each industry:

$$\Delta(TP - SP)_{Bonaire} = \sum_i \left(TTP_i * \Delta X_i\right) - \sum_i \left(TSP_i * \Delta X_i\right) \tag{5}$$

Hence, if the coral reefs around Bonaire degrade, causing direct tourism demand in some sectors to decline, both direct and indirect economic consequences are expected to occur. 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 GDP, using Eqs. (3), (4), and (5).

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Data Availability The data that support the findings of this study are available from the authors upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

References

Akpinar-Elci M, Sealy H (2014) Climate change and public health in small island states and Caribbean countries. In: Pinkerton KE, Rom WN (eds) Global climate change and public health. Humana Press, New York, NY, pp 279–292. https://link-springercom.vu-nl.idm.oclc.org/content/pdf/. https://doi.org/10.1007/978-1-4614-8417-2.pdf

Andersen OB, Knudsen P (2009) The DNSC08 mean sea surface and mean dynamic topography. J Geophys Res 114:C11. https://doi.org/10.1029/2008JC005179

Baban SM (2003) Responding to the effects of climate change on agriculture, fisheries and tourism in the Caribbean region utilising geoinformatics. Farm Bus J Caribbean Agro-Econ Soc 6(533–2016–38342):95–111

Bacharach M (1970) Biproportional matrices and input-output change. 16. Cambridge University Press Archive, Cambridge 1970. XII, 170 S

Bak RPM, Nieuwland G, Meesters EH (2005) Coral reef crisis in deep and shallow reefs: 30 years of constancy and change in reefs of Curacao and Bonaire. Coral Reefs 24(3):475–479. https://doi.org/10.1007/s00338-005-0009-1

BCQS International (2020) Caribbean & Latin America construction market trend report. Retrieved May, 2022, from: https://bcqs.com/2020/10/29/bcqs-releases-2020-caribbean-latinamerica-market-trend-report/

Bloemendaal N, Haigh ID, de Moel H, Muis S, Haarsma RJ, Aerts JCJH (2020) Generation of a global synthetic tropical cyclone hazard dataset using STORM. Scientific Data 7(1). https://doi.org/10.1038/s41597-020-0381-2

Buchhorn M, Smets B, Bertels L, De Roo B, Lesiv M, Tsendbazar N-E, Herold M, Fritz (2020) Copernicus global land service: land cover 100m: collection 3: epoch 2018: globe (V3.0.1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.3518038

Burke L, Maidens J (2004) Reefs at risk in the Caribbean. World Resources Institute, Washington D.C.

Carabine E, Dupar M (2014) The IPCC's fifth assessment report: what's in it for small island developing states? Climate & Development Knowledge Network. Retrieved May, 2022, from: https://cdkn.org/sites/default/files/files/CDKN_IPCC_Whats_in_it_for_SIDS.pdf

Chinowsky P, Helman J (2021) Protecting Infrastructure and public buildings against sea level rise and storm surge. Sustainability 13(19):10538. https://doi.org/10.3390/su131910538

Crabbe MJC (2008) Climate change, global warming and coral reefs: modelling the effects of temperature. Comput Biol Chem 32(5):311–314. https://doi.org/10.1016/j.compbiolchem.2008.04.001

Croes R, Rivera M, Semrad K, Shapoval V, van Niekerk M (2019) Bonaire: the first blue destination in the Caribbean. Rosen Research Review 1(2):13 https://stars.library.ucf.edu/rosen-research-review/vol1/iss2/13

Davis D, Tisdell C (1995) Recreational scuba-diving and carrying capacity in marine protected areas. Ocean & Coastal Management 26(1):19–40. https://doi.org/10.1016/0964-5691(95)00004-L

Díaz-Pérez L, Rodríguez-Zaragoza FA, Ortiz M, Cupul-Magaña AL, Carriquiry JD, Ríos-Jara E et al (2016) Coral reef health indices versus the biological, ecological and functional diversity of fish and coral assemblages in the Caribbean Sea. PLoS One 11(8):e0161812. https://doi.org/10.1371/journal.pone.0161812

Dullaart J, Muis S, Bloemendaal N, Chertova MV, Couasnon A, Aerts JC (2021) Accounting for tropical cyclones more than doubles the global population exposed to low-probability coastal flooding. Communications Earth & Environment 2(1):1–11. https://doi.org/10.1038/s43247-021-00204-9

Ezcurra P, Rivera-Collazo IC (2018) An assessment of the impacts of climate change on Puerto Rico's cultural heritage with a case study on sea-level rise. J Cult Herit 32:198–209. https://doi.org/10.1016/j.culher.2018.01.016

Federal Emergency Management Agency (FEMA) (2009) Hazus, multi-hazard loss estimation methodology, flood Model Hazus® -MH technical manual (2.1). Mitigation Division, Department of Homeland Security, Washington DC https://www.fema.gov/floodmaps/tools-resources/flood-map-products/hazus/user-technical-manuals

Ferrario F, Beck MW, Storlazzi CD, Micheli F, Shepard CC, Airoldi L (2014) The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat Commun 5(1):1–9. https://doi.org/10.1038/ncomms4794

Foley A (2010) Uncertainty in regional climate modelling: a review. Progress in Physical Geography: Earth and Environment 34(5):647–670. https://doi.org/10.1177/0309133310375654

Frechtling DC, Horváth E (1999) Estimating the multiplier effects of tourism expenditures on a local economy through a regional input-output model. J Travel Res 37(4):324–332

Furtuoso MCO, Guilhoto JJM (2000) Using input-output to measure the GDP and to estimate monthly growth Rates of productive complexes: the case of the Brazilian agribusiness. Soc Sci Res Netw. https://doi.org/10.2139/ssrn.2417389

García Sánchez F, García Sánchez H, Ribalaygua C (2020) Cultural heritage and sea level rise threat: risk assessment of coastal fortifications in the Canary Islands. J Cult Herit 44:211–217. https://doi.org/10.1016/j.culher.2020.02.005

Garner GG, Hermans T, Kopp RE, Slangen ABA, Edwards TL, Levermann A, Nowikci S, Palmer MD, Smith C, Fox-Kemper B, Hewitt HT, Xiao C, Aðalgeirsdóttir G, Drijfhout SS, Edwards TL, Golledge NR, Hemer M, Kopp RE, Krinner G, Mix A, Notz D, Nowicki S, Nurhati IS, Ruiz L, Sallée J-B, Yu Y, Hua L, Palmer T, Pearson B (2021) IPCC AR6 sea-level rise projections. Version 20210809. PO.DAAC, CA, USA. Dataset accessed [2022-04-15] at https://podaac.jpl.nasa.gov/announcements/2021-08-09-Sea-level-projections-from-the-IPCC-6th-Assessment-Report

Garschagen M, Hagenlocher M, Comes M, Sabelfeld R, Lee YJ, Grunewald L, Lanzendörfer M, Mucke P, Neuschäfer O, Pott S, Post J, Schramm S, SchumannBölsche D, Vandemeulebroecke B, Welle T, Birkmann J (2016) World risk report 2016: the importance of infrastructure. United Nations University Institute for Environment and Human Security. Retrieved May, 2022, from: https://www.preventionweb.net/publication/worldrisk-report-2016-importance-infrastructure

GEBCO_2021 Grid (2021) GEBCO bathymetric compilation group. https://doi.org/10.5285/c6612cbe-50b3-0cff-e053-6c86abc09f8f

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

Hersbach H, Bell B, Berrisford P, Biavati G, Horányi A, Muñoz Sabater J, Nicolas J, Peubey C, Radu R, Rozum I, Schepers D, Simmons A, Soci C, Dee D, Thépaut JN (2022) ERA5 hourly data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.adbb2d47. Accessed 14–04–2022

Hoegh-Guldberg O, Bruno JF (2010) The impact of climate change on the world's marine ecosystems. Science 328(5985):1523–1528 https://www.jstor.org/stable/40656421

Hoegh-Guldberg O, Poloczanska ES, Skirving W, Dove S (2017) Coral reef ecosystems under climate change and ocean acidification. Front Mar Sci 4:158. https://doi.org/10.3389/fmars.2017.00158

IPCC (2021) Climate change 2021: the physical science basis. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/9781009157896

IPCC (2022) Climate change 2022: impacts, adaptation, and vulnerability. In: Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, NY, USA, p 3056. https://doi.org/10.1017/9781009325844

IPCC AR6 Sea Level Projection Tool (2021) IPCC. https://sealevel.nasa.gov/data_tools/17

Jaafar H, Ahmad F, El Beyrouthy N (2019) GCN250, global curve number datasets for hydrologic modeling and design. Sci Data 6:145. https://doi.org/10.6084/m9.figshare.7756202.v1

Junius T, Oosterhaven J (2003) The solution of updating or regionalizing a matrix with both positive and negative entries. Econ Syst Res 15:87–96. https://doi.org/10.1080/0953531032000056954

Knapp KR, Kruk MC, Levinson DH, Diamond HJ, Neumann CJ (2010) The international best track archive for climate stewardship (IBTrACS): unifying tropical cyclone best track data. Bull Am Meteorol Soc 91:363–376. https://doi.org/10.1175/2009BAMS2755.1

Koks E, van Zanten B (2015) Technical Manual GEM Tool Bonaire. Institute for Environmental Studies VU University Amsterdam, the Netherlands. Wolfs Company, Bonaire, Caribbean Netherlands

Kramer P, McField M, Álvarez Filip L, Drysdale I, Flores MR, Giró A, Pott R (2015) 2015 Report card for the Mesoamerican Reef. Retrieved May, 2022, from: www.healthyreefs.org

Lal M, Harasawa H, Takahashi K (2002) Future climate change and its impacts over small island states. Clim Res 19:179–192. https://doi.org/10.3354/cr019179

Leijnse T (2022) SFINCS documentation. Retrieved May, 2022, from: https://sfincs.readthedocs.io/_/downloads/en/latest/pdf/

Leijnse T, van Ormondt M, Nederhoff K, van Dongeren A (2021) Modeling compound flooding in coastal systems using a computationally efficient reducedphysics solver: Including fluvial, pluvial, tidal, wind-and wave-driven processes. Coast Eng 163:103796. https://doi.org/10.1016/j.coastaleng.2020.103796

Lenzen M, Gallego B, Wood R (2009) Matrix balancing under conflicting information. Econ Syst Res 21(1):23–44. https://doi.org/10.1080/09535310802688661

Leontief WW (1951) Input-output economics. Sci Am 185(4):15–21 https://www.jstor.org/stable/24945285

Lin BB, Khoo YB, Inman MB, Wang C, Tapsuwan S, Wang X (2014) Assessing inundation damage and timing of adaptation: sea level rise and the complexities of land use in coastal communities. Mitig Adapt Strateg Glob Chang 19(5):551–568. https://doi.org/10.1007/s11027-013-9448-0

Macpherson C, Akpinar-Elci M (2013) Impacts of climate change on Caribbean life. Am J Public Health 103(1):e6. https://doi.org/10.2105/2FAJPH.2012.301095

Mayer M, Vogt L (2016) Economic effects of tourism and its influencing factors. Zeitschrift für Tourismuswissenschaft 8(2):169–198. https://doi.org/10.1515/tw-2016-0017

Meesters EH, Becking LE, van der Geest M (2019) Achteruitgang koraalriffen Caribisch Nederland: oorzaken en mogelijke oplossingen voor koraalherstel. (Wageningen Marine Research rapport; No. C061/19). Wageningen Marine Research. https://doi.org/10.18174/496168

Mimura N, Nurse L, McLean RF, Agard J, Briguglio L, Lefale P, Payet R, Sem G (2007) Small islands. Climate change 2007: impacts, adaptation and vulnerability. In: Parry ML et al (eds) Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 687–716

Monioudi I, Asariotis R, Becker A, Bhat C, Dowding-Gooden D, Esteban M, Feyen L, Mentaschi L, Nikolaou A, Nurse L, Phillips W, Smith D, Satoh M, Trotz UO, Velegrakis AF, Voukouvalas E, Vousdoukas MI, Witkop R (2018) Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia. Reg Environ Chang 18(8):2211–2225. https://doi.org/10.1007/s10113-018-1360-4

Muis S, Apecechea MI, Dullaart J, de Lima RJ, Madsen KS, Su J et al (2020) A high-resolution global dataset of extreme sea levels, tides, and storm surges, including future projections. Front Mar Sci 7:263. https://doi.org/10.3389/fmars.2020.00263

Nederhof K (2022) We willen maximaal 250.000 bezoekers per jaar. De Telegraaf. Retrieved May, 2022 from: https://www.telegraaf.nl/nieuws/1286606539/bonaire-is-massatoerisme-beu-we-willen-maximaal-250-000-bezoekers-per-jaar

Nirandjan S, Koks EE, Ward PJ, Aerts JCJH (2022) A spatially-explicit harmonized global dataset of critical infrastructure. Scientific Data 9(1). https://doi.org/10.1038/s41597-022-01218-4

Nurse LA, McLean MF, Agard J, Briguglio LP, Duvat-Magnan V, Pelesikoti N, Tompkins E, Webb A (2014) Small islands. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1613–1654 https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap29_FINAL.pdf

Pandolfi JM, Connolly SR, Marshall DJ, Cohen AL (2011) Projecting coral reef futures under global warming and ocean acidification. Science 333:418–422. https://doi.org/10.1126/science.1204794

Peachey DR (1986) Modeling waves and surf. ACM Siggraph Computer Graphics 20(4):65–74. https://doi.org/10.1145/15922.15893

Pessoa J, Deloumeaux L, Ellis S (2009) The 2009 UNESCO Framework for Cultural Statistics (FCS). UNESCO Institute for Statistics. Retrieved December, 2022, from: https://www.spc.int/DigitalLibrary/Get/vayzx

Ravanelli R, Riguzzi F, Anzidei M, Vechio A, Nigro L, Spagnoli F, Crespi M (2019) Sea level rise scenario for 2100 A.D. for the archaeological site of Motya. Rendiconti Lincei Scienze Fisiche e Naturali 30:747–757. https://doi.org/10.1007/s12210-019-00835-3

Rhiney K (2015) Geographies of Caribbean vulnerability in a changing climate: issues and trends. Geogr Compass 9(3):97–114. https://doi.org/10.1111/gec3.12199

Rider Levett Bucknall (2021) Caribbean report construction market intelligence. Retrieved May, 2022, from: https://s31756.pcdn.co/americas/wp-content/uploads/sites/4/2021/06/2021-Caribbean-Report.pdf

Robinson S-A (2018) Climate change adaptation in small island developing states: insights and lessons from a meta-paradigmatic study. Environ Sci Pol 85:172–181. https://doi.org/10.1016/j.envsci.2018.03.030

Scandurra G, Romano AA, Ronghi M, Carfora A (2018) On the vulnerability of small island developing states: a dynamic analysis. Ecol Indic 84:382–392. https://doi.org/10.1016/j.ecolind.2017.09.016

Schep S, van Beukering P, Brander L, Wolfs E (2013) The tourism value of nature on Bonaire. IVM Institute for Environmental Studies. https://www.dcbd.nl/sites/default/files/documents/Tourism-Value-Bonaire.pdf

Sesana E, Gagnon AS, Ciantelli C, Cassar J, Hughes JJ (2021) Climate change impacts on cultural heritage: a literature review. Wiley Interdiscip Rev Clim Chang 12(4). https://doi.org/10.1002/wcc.710

Sheppard C, Dixon DJ, Gourlay M, Sheppard A, Payet R (2005) Coral mortality increases wave energy reaching shores protected by reef flats: examples from the Seychelles. Estuar Coast Shelf Sci 64(2–3):223–234. https://doi.org/10.1016/j.ecss.2005.02.016

Sookram S (2009) The impact of climate change on the tourism sector in selected Caribbean countries. Caribbean Development Report 2(30):204–225

Spalding MD, Ravilious C, Green EP (2001) World Atlas of coral reefs. Prepared at the UNEP world conservation monitoring centre. University of California Press, Berkeley, USA. https://ia600301.us.archive.org/19/items/worldatlasofcora01spal/worldatlasofcora01spal.pdf

Spies J, Soons A, Thodé G, Verhey L, Weekers F (2015) Vijf jaar verbonden. Evaluatie Caribisch Nederland, Bonaire, Sint Eustatius, Saba en Europees Nederland

Statistics Netherlands (CBS) (2012) Toerisme Caribisch Nederland 2012. Retrieved from: https://www.cbs.nl/nlnl/achtergrond/2014/23/toerisme-caribisch-nederland-2012

Statistics Netherlands (2018) 3/4 of young Bonairians not in education are in work. Retrieved from: https://www.cbs.nl/engb/news/2018/08/3-4-of-young-bonairians-not-in-education-are-in-work

Steenge AE, Van De Steeg A (2010) Tourism multipliers for a small Caribbean Island State: the case of Aruba. Econ Syst Res 22(4):359–384. https://doi.org/10.1080/09535314.2010.526926

Stone R (1961) Input-output and national accounts. Organisation for European Economic Co-operation.

Taylor MA, Clarke LA, Centella A, Bezanilla A, Stephenson TS, Jones JJ et al (2018) Future Caribbean climates in a world of rising temperatures: the 1.5 vs 2.0 dilemma. J Clim 31(7):2907–2926. https://doi.org/10.1175/JCLI-D-17-0074.1

Taylor MA, Stephenson TS, Chen AA, Stephenson KA (2012) Climate change and the Caribbean: review and response. Caribb Stud 40(2):169–200 http://www.jstor.org/stable/41917607

Thomas A, Benjamin L (2020) Non-economic loss and damage: lessons from displacement in the Caribbean. Clim Pol 20(6):715–728. https://doi.org/10.1007/s10113-017-1184-7

Tol SJ (2018) The economic impacts of climate change. Rev Environ Econ Policy 12(1):4–25. https://doi.org/10.1093/reep/rex027

Tourism Corporation Bonaire (TCB) (2008) Bonaire tourism, annual statistics report 2008. Kralendijk, Bonaire. Retrieved from: https://bonaireisland.com/wp-content/uploads/2022/08/Annual-Statistics-Report-2010.pdf

United Nations Department for Economic and Social Information and Policy Analysis and World Tourism Organization (1994) Recommendations on tourism statistics. United Nations. Herein referred to as "UN, 1994", New York

United Nations Office for Disaster Risk Reduction (NDRR) (2015) Hazard. Retrieved November 2022, from: https://www.undrr.org/terminology

Uyarra MC, Cote IM, Gill JA, Tinch RR, Viner D, Watkinson AR (2005) Island specific preferences of tourists for environmental features: implications of climate change for tourism-dependent states. Environ Conserv 32(1):11–19

van Beukering P, Brander L, Tompkins E, McKenzie E (2007) Valuing the environment in small islands. Joint Nature Conservation Committee, Peterborough, GB, p 125 https://eprints.soton.ac.uk/349072/

van der Lely JAC, van Beukering P, Muresan L, Cortes DZ, Wolfs E, Schep S (2013) The total economic value of nature on Bonaire. IVM Institute for Environmental Studies, Amsterdam https://www.dcbd.nl/sites/default/files/documents/Total-Economic-Value-of-Nature-of-Bonaire.pdf

Vousdoukas MI, Mentaschi L, Voukouvalas E, Verlaan M, Jevrejeva S, Jackson LP, Feyen L (2018) Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nat Commun 9(1):1–12. https://doi.org/10.1038/s41467-018-04692-w

Walther G (2010) Community and ecosystem responses to recent climate change. Philos Trans R Soc B 365(1549):2019–2024. https://doi.org/10.1098/rstb.2010.0021

Wang Y (2020) Coastal and marine environments (2de editie). CRC Press, p 388. https://doi.org/10.1201/9780429441004

Wiedmann T, Lenzen M, Turner K, Barrett J (2007) Examining the global environmental impact of regional consumption activities—part 2: review of input– output models for the assessment of environmental impacts embodied in trade. Ecol Econ 61(1):15–26

Wolfs E, Schep S, Luján V, van Beukering P (2015) What is Bonaire's cruise tourism worth? Institute for Environmental Studies VU University Amsterdam, the Netherlands, Wolfs Company, Bonaire. Retrieved on May, 2022, from: https://www.dcbd.nl/sites/default/files/documents/What%27s%20Bonaire%27s%20Cruise%20Tourism%20Worth%20-%20Aug%202015_.pdf

World Bank (2021) COVID-19 post-disaster assesment Bonaire, socioeconomic assessment, March – December 2020. Retrieved from: https://bonairegov.com/fileadmin/user_upload/WorldBank-PDNA-SI.pdf

Yamazaki D, Ikeshima D, Sosa J, Bates PD, Allen GH, Pavelsky TM (2019) MERIT hydro: a high-resolution global hydrography map based on latest topography dataset. Water Resour Res 55(6):5053–5073. https://doi.org/10.1029/2019WR024873

Zellentin A (2015) Climate justice, small island developing states & cultural loss. Climate Change 133(3):491–498. https://doi.org/10.1007/s10584-015-1410-6