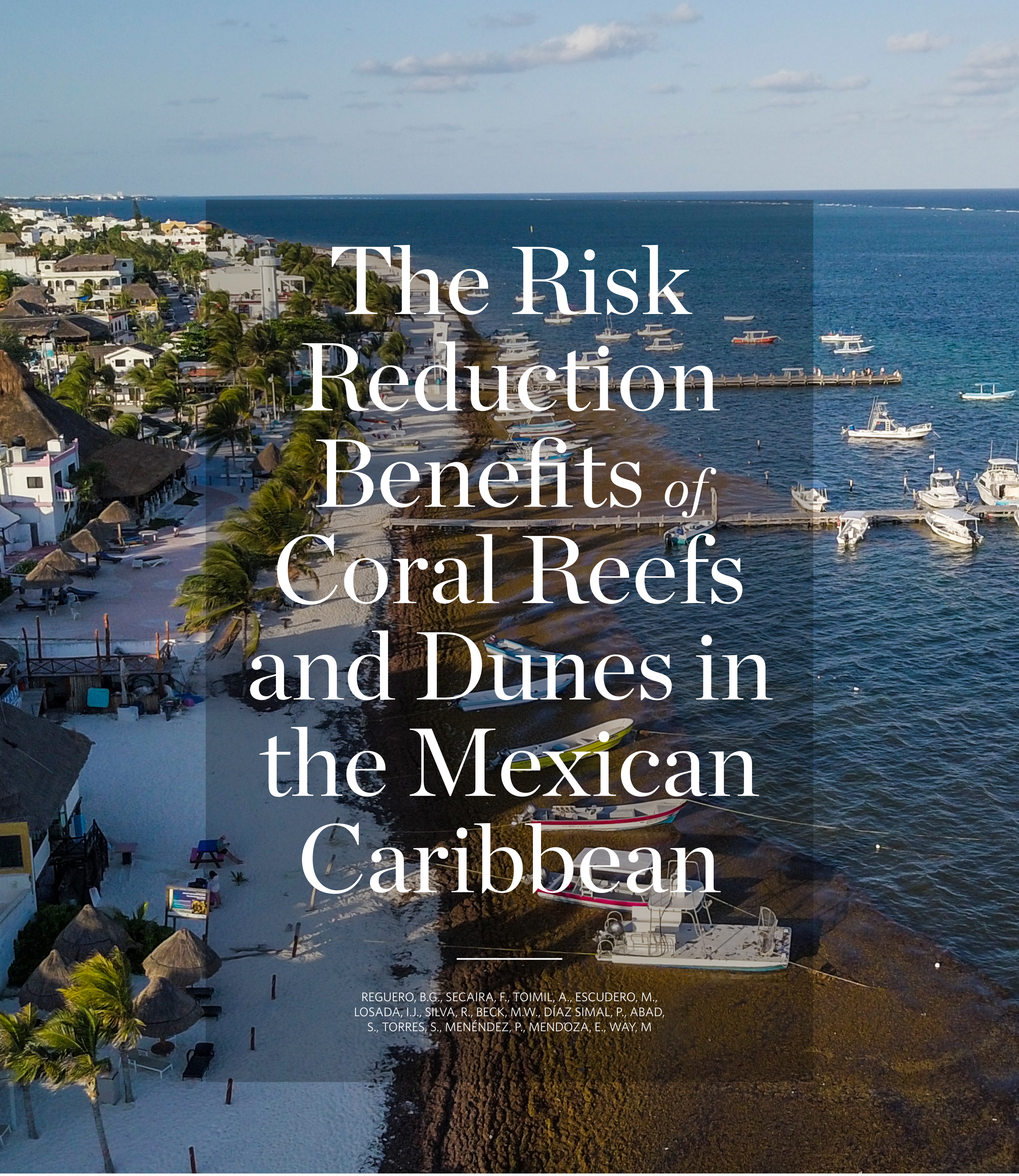

The Risk Reduction Benefits *of* Coral Reefs and Dunes in the Mexican Caribbean

REGUERO, B.G., SECAIRA, F., TOIMIL, A., ESCUDERO, M., LOSADA, I.J., SILVA, R., BECK, M.W., DÍAZ SIMAL, P., ABAD, S., TORRES, S., MENÉNDEZ, P., MENDOZA, E., WAY, M

The Nature Conservancy

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The Risk Reduction Benefits of Coral Reefs and Dunes in the Mexican Caribbean - Technical Report

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Photograph on the cover:
Fernando Secaira, Jennifer Alder @ The Nature Conservancy. Red Mangrove (Rhizophora mangle) grows along the edge of Baie Liberté, Haiti.

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The information is available online at www.coastalresilience.org

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The analysis was conducted in 2017 and 2018.

A scientific article with further details was published in 2019 and can be found in Reguero et al (2019), at: https://www.frontiersin.org/articles/10.3389/feart.2019.00125/full

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Highlights of the reefs and dunes risk reduction benefits

Coral reefs and dune systems provide substantial risk reduction benefits to people and property, and the loss of just one meter of reef crest or dune height can significantly increase risk. Coral reef and dune conservation and restoration could, therefore, be an important part of the solution for reducing risks from natural hazards in Quintana Roo and around the globe.

This report provides a social and economic valuation of the protection provided by reefs and dunes to people, infrastructure and the tourism industry in Quintana Roo to inform coastal development policies and practices in the Mesoamerican Reef. This information is relevant to the tourism, real estate, risk reduction, and conservation sectors as they seek to identify sustainable and cost-effective approaches for risk reduction.

Figure 1
A narrow coastal strip, located between the Caribbean and inland lagoons in the Sian Ka'an Biosphere Reserve in Quintana Roo, is highly vulnerable to hurricanes. © Christiana Ferris/TNC

By showing the spatial variation of the flood reduction benefits between sections of coastline with and without reefs and/or dunes, these results identify the places where reef management may yield the greatest returns. Furthermore, by valuing coastal protection benefits in terms used by finance and development decision-makers (e.g., expected socio-economic benefits), these results can be readily used alongside common metrics to inform risk reduction, development, and environmental and conservation decisions.

The study revealed that dunes and reefs provide significant and financially valuable flood protection to people and coastal property. Risk reduction benefit is the difference between the losses caused by a storm to people and infrastructure protected by existing reefs and dunes, and the losses caused by the same storm but without the reefs and dune. Built-stock is the sum of the value of all buildings located in the area of analysis.

The main findings were:

PEOPLE PROTECTED BY REEFS

People in the study area:

307,640

People in sections protected by reefs:

105,800

BUILT-STOCK PROTECTED BY REEFS

Built-stock in the study area:

USD 3.4 billion.

Built-stock in sections protected by reefs:

USD 858 million.

Benefits for sections with reefs:

The annualized number of people flooded would increase **by 35%, from 13,093 to 17,679 per year.**

Annualized number of people protected is **4.3% of the 105,800** people in sections protected by reefs.

During a 1-in-100-year storm **8.3% of people** living behind reef are protected.

Expected annual losses would almost triple as they increase **by 178%, from USD 9.2 million** with current reefs to **USD 25.5 million** with degraded reefs.

Losses during **a 1-in-100-year** storm almost double as they increase **by 74% from USD 136** million to USD 237 million.

Avoided losses during a **1-in-100 years** storm account for **11.6%** of the value of all built-stock behind reefs.

HOTEL INFRASTRUCTURE PROTECTED BY REEFS

Value of hotels built in the study area:

USD 1.5 billion.

Value of hotels built in sections protected by reefs:

USD 957 million.

RISK REDUCTION PROVIDED BY DUNES

Expected annual losses to hotels would increase by

173%, from USD 12 million to USD 32.8 million.

Losses during a

1-in-100-year

storm would increase by 91% increase from USD 288 million to

USD 550 million.

Avoided losses would increase by

139% and 131%

with 1-in-25 and 50-year storms, respectively.

Avoided losses during a 1-in-100 years storm account for

30 %

of the value of all hotels behind reefs.

Avoided losses during a 1-in-500 years storm account for

50%

of the value of all hotels

The expected annual risk reduction benefits from dunes is estimated at

USD 16.7 million.

The annual risk reduction benefits from dunes alone are similar to benefits from reefs, which is

USD 12 million.

Dunes provide critical protection from frequent storms. Dune reduces risk by

63%, 45% and 42%

for 1-in-10 and 1-in-25 and 1-in-50-year storms respectively.

2

Introduction

Coastal zones are some of the most risk-prone areas of the world. Coastal development and climate change are dramatically increasing the risks of flooding and erosion caused by extreme weather events for people, infrastructure, and the economy. Although coastal ecosystems protect people and property from storms, they are typically not accounted for in coastal planning and management, and therefore continue to be degraded at alarming rates.

The Nature Conservancy (TNC) conducted this study to measure the economic benefits provided by reefs and dunes in Quintana Roo, also referred to as the Mexican Caribbean, focusing on the benefits to the local population, infrastructure, and tourism industry. Protected by the Mesoamerican Reef, this area is the top tourist destination in Mexico and is at high risk from devasting hurricanes.

2.1 Coastal area at risk

Erosion, flooding, and extreme weather events affect hundreds of millions of people, infrastructure, and economic activity worldwide. The impacts of coastal hazards, such as hurricanes, can be devastating to coastal economies and will continue to worsen with climate change and poorly planned coastal development (Wong et al. 2014; Hallegatte et al. 2013; Reguero et al. 2015; Reguero et al. 2019).

Hurricanes Harvey, Irma and Maria cost the insurance industry a record amount in 2017, which became the costliest hurricane season on record with USD 215 billion in losses, including uninsured losses. Globally, the losses from weather-related catastrophes amounted to more than USD 330 billion in 2017, the highest weather-related losses ever recorded (Munich Re NatCat Service).

2.2 The role of coral reefs and dunes in coastal protection

Coral reefs and dunes provide natural protection from waves, wind and storm surges (Beck & Lange 2016; Narayan et al. 2016; Reguero et al. 2021). It has been estimated that 197 million people live within 50 kilometers of a reef and benefit from their ecosystem services (Ferrario et al. 2014). Healthy reefs are natural submerged structures that can provide significant coastal protection and flood risk reduction benefits (Beck et al. 2018). Coral reefs naturally protect our coasts by attenuating and redistributing wave energy and supplying sediment on adjacent beaches (Sheppard et al. 2005a; Gallop et al. 2014).

Wave energy is released when hitting the beach and dunes both under normal conditions and during storms. Undisturbed dunes are sand reservoirs which are washed away during storms but return to the coast when climate conditions return normal.

The friction of coral reefs in conjunction with wave breaking on the reef crests, as shown in Figure 2, results in high rates of wave energy dissipation over relatively short distances (Lowe et al. 2005; Monismith et al. 2015). A coral reef's complex bathymetry can also cause waves to change direction and velocity. The shoreline and the coastal landforms are shaped by the effects of reefs on wave energy propagation.

Despite providing a critical value to coastal communities, the coastal protection service of these natural structures is rarely accounted for in coastal planning and decision-making. The lack of quantification and valuation in spatially-explicit economic terms prevents the inclusion of coral reefs as coastal infrastructure in risk management (Beck et al. 2018; Reguero et al. 2019). Until recently, most flood risk management involved conventional engineering measures, but some recent experiences show that reefs can be used effectively and engineered for coastal protection while also providing other services (Reguero et al. 2018a; Chavez et al. 2021; Silva et al. 2021).

The shoreline and the coastal landforms are shaped by the effects of reefs on wave energy propagation.

Economic valuations of the protective services that coastal habitats provide can inform coastal management decisions, enhance reef conservation, and build the resilience of the communities reefs protect by offering cost-effective options that reduce risk.

Figure 2
Coral reefs, like the one of Puerto Morelos, induce waves to break and their energy to dissipate. © Jennifer Alder/TNC

Figure 3
Coral reef architecture is key to providing hydrodynamic roughness and to wave breaking. Photo: The Nature Conservancy.

However, coastal ecosystems have been severely degraded, 30% of coral reefs have been lost globally, while 75% of the world's coral reefs are rated as threatened (Burke et al. 2011). Corals are threatened by disease, thermal stress, bleaching, physical destruction, fewer herbivores, ocean acidification, and increased sediment loads (Bjorn et al. 1986; Gardner et al. 2003; Mumby et al. 2007; Barbier et al. 2011), threats exacerbated by climate change.

Coral loss also translates into the loss of architectural complexity, which will likely have serious consequences for reef biodiversity, ecosystem functioning, and associated environmental services (Alvarez-Filip et al. 2009). Damage to this coastal infrastructure reduces its ability to protect the coast and to provide vital ecosystem services.

2.3 Coastal infrastructure in Quintana Roo, Mexico.

Twelve million tourists visit reefs, beaches, and lagoons in the State of Quintana Roo every year. In 2019, the State's tourism industry generated USD 15 billion (Secretaría de Turismo del Estado de Quintana Roo), making it the top tourist destination in Mexico.

The coastal areas of Quintana Roo have been subject of significant and continuous development since the 1970s (see Figure 4 and Figure 5). According to our analysis, there are more than 100,000 hotel rooms and over 900 hotels in the coastal zone, and over 200 hotels with beachfront .

The damages caused by hurricanes to this valuable infrastructure have been significantly reduced by coral reefs and dunes. Storm surge from Hurricane Wilma was reduced from 14 meters in the open ocean to 2 meters inside the Puerto Morelos reef lagoon, fully sparing the coastal area from storm damage (Blanchon et al. 2010).

However, dunes and reefs are at risk. Live coral cover has been reduced from 40% in the early 1970s to 8-10% by 2010s. As in other coastal areas around the world, the local population and economy that benefit directly from the reefs and dunes – also pose a major threat to their health. Hence, the importance of measuring the risk reduction benefits provided by reefs and dunes to inform policies and coastal development practices in Quintana Roo.

2.4 Assessing the coastal protection value of the Mesoamerican Reef in Quintana Roo

This study assesses the risk reduction benefits for people, infrastructure, and the economy provided by the Mesoamerican Reef in Quintana Roo. Benefits are assessed as the difference between avoided losses from storms under current reef conditions and with a 1-meter loss of reef crest. (Figure 6). Benefits are expressed in annualized avoided losses for storms of various sizes and probabilities of occurrence.

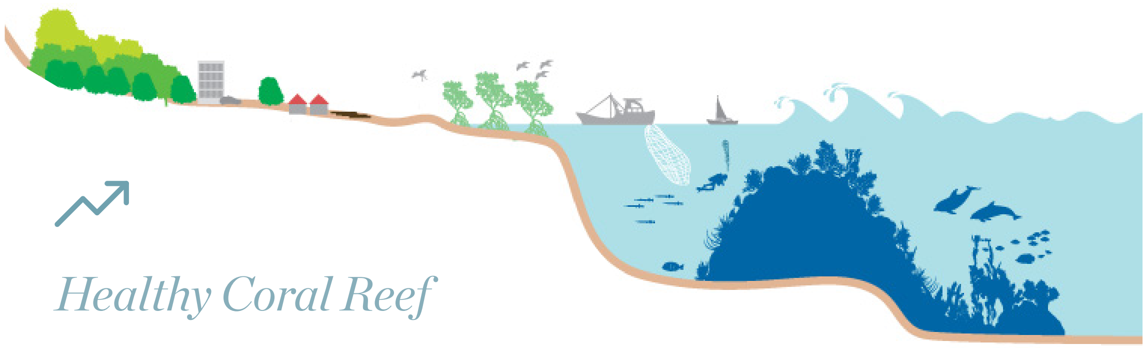
Benefits are expressed in annualized avoided losses for storms of various sizes and probabilities of occurrence.

A valuation of protective services provided by reefs and coastal dunes was conducted to reflect their *combined* effect in providing flood protection. In many places, mangroves also provide flood protection, however, in Quintana Roo, mangroves are located to far inland to provide coastal protection and, therefore, were not considered in this study.

Figure 4
Hotels in Cancún, Quintana Roo in 1985 (left) and in 2015 (right). Source: Secretary of Economy, Mexico.

Figure 5
Typical beachfront hotel development in Quintana Roo. Source: Hotels.com

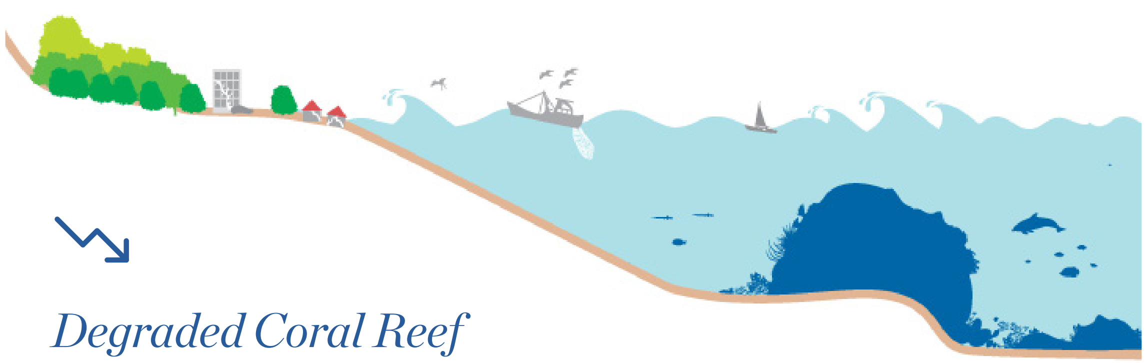
Figure 6. Conceptual representation of the natural protection provided by coral reefs (above). Degradation of reef crest leads to less flood protection and increases risk (below). This protective service can be quantified in terms of the risks and economic losses they avert. Source: Beck et. al., 2012. World Risk Report 2012.



Healthy Coral Reef

A healthy reef crests near the surface and serves as a major natural break - water - reducing most wave energy and helping protect coastal communities. Healthy reefs have abundant living corals, and support fishing industries and diving.

In coastal areas where wave energy is lower, mangroves can grow and further stabilize shorelines, reduce erosion, and provide nursery habitat for fish, shrimp and crabs.



Degraded Coral Reef

When reefs are degraded, the living corals die and the reef is eroded to rubble. As a result, much more wave energy passes over the reef, which erodes shorelines, increases risk of damage to people and property, reduces fishing and diving, and may force coastal communities to retreat, or pay for expensive coastal defenses like seawalls.

3

Data sources and methods

This section provides an overview of data sources and methods used in this analysis. Additional details can be found in Annexes I through IV.

The study follows a **probabilistic risk quantification framework** (SwissRe 2011; Reguero et al. 2018b) to identify the value that coral reefs and dunes provide in flood protection (Beck & Lange 2016; Whelchel et al. 2018).

Commonly used terms for the assessment and framework, include:

- **Annualized Expected Damages (AED):** the AED for each return period (RP) are the sum of the damages of all storms divided by the probability of the storm (return period).
- **Assets or built-stock:** the value of the buildings and other assets (residential, commercial, industrial, and hotel).
- **Flood depth:** the difference between flood level and ground level.
- **Flood level:** the water level in relation to mean sea level.
- **Flood prone coastal zone:** the area below 20 meters above mean sea level and less than 5 kilometers from the coastline.
- **Hazard:** the event or phenomena that causes damages. Each hazard can be described by its location, frequency, and intensity.
- **Damages curve:** the statistical correlation of flood level and severity of the damage. Damages are expressed as a percentage of the value of the asset impacted.
- **Exposure curve (floods):** the value of assets or number of people that would be impacted by different flood depths.
- **Mexican Caribbean:** the coastal area of Mexico bordering the Caribbean Sea, spanning from Cabo Catoche to the Mexico-Belize border.
- **Mesoamerican Reef:** the 1,000 kms (600 miles) of complex coral reef structures spanning from yhe Northern tip of the Mexican Caribbean (Cabo Catoche), through Belize and Guatemala, to the Bay Islands in Honduras.
- **Losses to assets:** the quantification of the economic losses caused by physical damages to assets.
- **People impacted:** the quantification of people living in the areas affected by flooding.
- **Risk reduction benefits from reefs:** the flood losses averted by reefs. Benefits are the difference between the amount of people and built-stock affected by flood levels under a scenario with reefs and a scenario with degraded reefs. Degraded reefs were modeled with a 1-meter loss of reef crest height.

- **Risk reduction benefits from dunes:** the flood losses averted by dunes. Benefits are the difference between the amount of people and built-stock affected by flood levels under a scenario with dunes and a scenario without dunes.

- **Risks:** the aggregation of the potential losses that all possible events may cause, weighted by the estimated frequency of events.

- **Study area:** the coastal area of Quintana Roo, Mexico, with data available to model scenarios. It excludes Cozumel Island.

- **Significant wave height (Hs):** is defined as the average wave height, from trough to crest, of the highest one-third of the waves.

- **Total Water Level (TWL):** the height of the water level in the sea, resulting from the combination of storm surge and wave heights and the modification caused by nearshore bathymetry, when surge and waves approach the coastline.

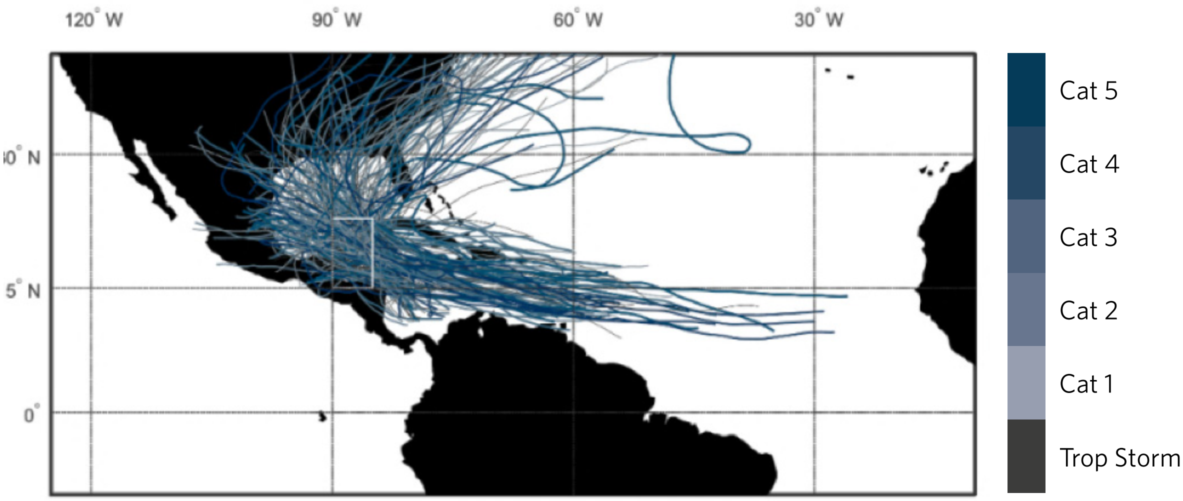
Mexico Reef Akumal © Fernando Secaira TNC

Figure 7. Key steps and critical data needed to quantify risk. Source: adapted from (Reguero et al. 2018b)

	Hazard	Socioecomic Exposure	Vulnerability	RISK
	How strong? **How frequent?**	**Where?** **What?** **How many?**	**How well built?**	

	Hazard	Socioecomic Exposure	Vulnerability	RISK
Data	• Historical storms in the Caribbean. • Caribbean and QR bathymetry.	• Population data (WorldPop and Census data). • Economic Census data. • Hotel distribution and built footprint.	• Specific vulnerability curves for built stock, hotel and population.	• Damages from each storm.
Methods	1. Probabilistic simulations of tropical storms. 2. Wind, Surge and Wave fields calculation fot each storm. 3. Calculation of total water levels onshore. 4. Reef model to assess floofing inland.	1. Spatial downscaling of population and built capital (100m). 2. Digitalization of hotel built footprint and beach characteristics from saletite imagery. 3. Creation of database on characteristics and exposure of hotels (location, number or rooms, hotel category, average price, etc.) from oline queries and survey.	1. Calculate historical damages for historical storms from the combination of flooding ectent, exposed assets, and vulnerability curves. 2. Calibration of historial damages from reported damages for historical storms (e.g. Hurricane Dean). 3. Calibration of exposure (built capital and hotel exposure) to reproduce historial damages. 4. Recalculation of damages for each storm and each type of asset; built stock (residential, commercial, and industrial facilities); hotels; and population. 5. Calculation for the scenario with ecosystem and without ecosystems.	1. Probabilistic analysis of damages to define economic value and population impacted by each storm. 2. Statistical definition of damages associated with certain return periods. 3. Calculation of the benefit as the difference in risk between the two scenarios (with and without the ecosystems). 4. Calculation of Annualized Expected Damages and Benefits, by integrating the probability of each simulated event.

Figure 8. Simulated hurricane tracks in the region of Quintana Roo.



The process we used to quantify risk is outlined in Figure 7 and 13 and can be summarized in this sequence of steps:

Step 1. Hazard modeling

Hazards were calculated using a probabilistic simulation of storms in the Caribbean. Probabilistic simulations are recommended for assessing risk in situations with limited observations, like coastal flooding from hurricanes (Resio & Irish 2015). A probabilistic simulation generates thousands of possible events that could occur during a certain period. Historical wind, wave, and storm surge data from ~900 storms were used to calibrate ~15,000 synthetic storms (see Figure 8). Comparatively, deterministic approaches study one or only a few individual storm events. The simulations were used to calculate the Total Water Levels (combined storm surge and wave heights) along the coast of Quintana Roo.

The probabilistic analysis of storms was conducted using the CLIMADA risk model, a component of the Economics of Climate Adaptation (ECA) framework. CLIMADA[2] is an open-source climate adaptation assessment modelling platform that employs state-of-the-art probabilistic modeling, allowing users to estimate expected economic damage, additional damage derived from an increase in the value of the assets, and additional damages due to the impacts of climate change. The Economics of Climate Adaptation methodology provides a practical framework that national and local officials can use to quantify the risk that climate change poses to their economies and to assess costs/benefits of specific risk reduction measures.

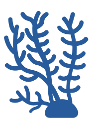
2. https://climada-python.readthedocs.io/en/stable/tutorial/1_main_climada.html

Step 2. Flood modeling and the role of the ecosystems

The Total Water Levels generated by each storm are used to calculate inland flooding using Xbeach, a numerical model for wave propagation that has been extensively validated for reef environments. Xbeach includes the effect of reefs and the non-linear effects of flooding from storms (Reguero et al. 2021; Van Dongeren et al. 2013; Quataert et al. 2015). The study area was divided in transects, each every 200 m perpendicular to the coastline. (Figure 9).

The use of coastal transects neglects some of the hydrodynamics that occur on natural reefs, such as lateral flow which is the effect of waves when they run in many directions (Figure 11).

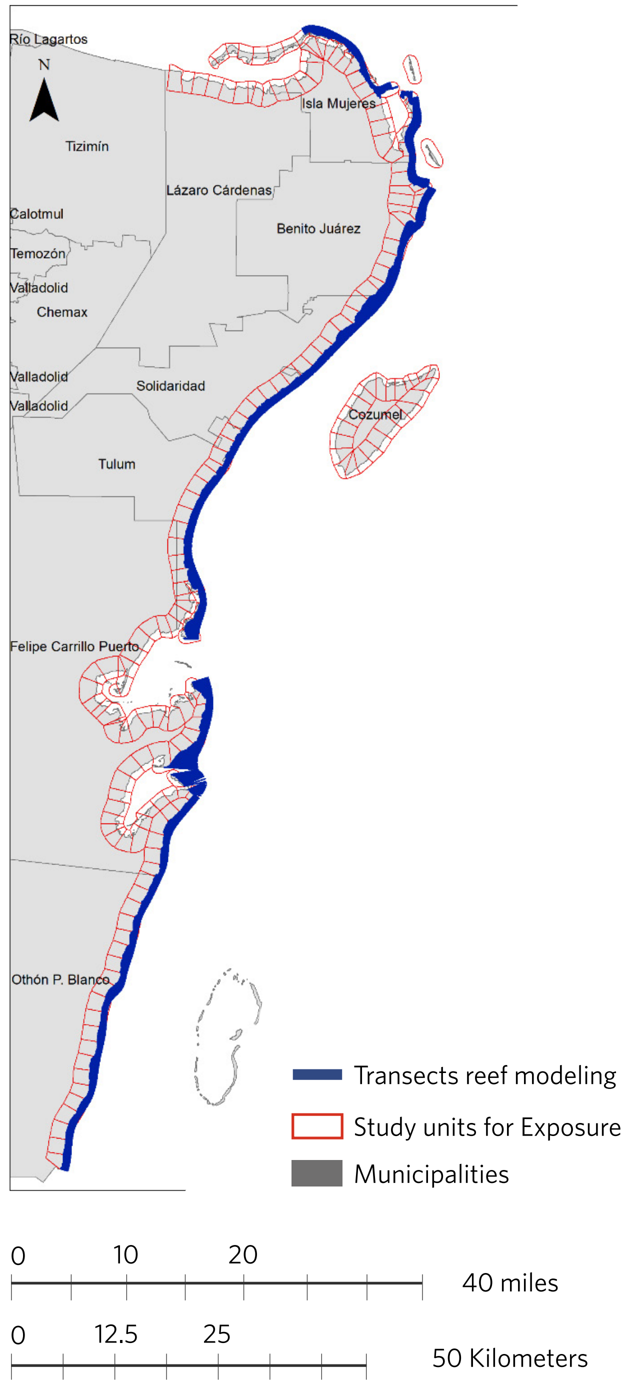
Flood modeling was performed for two scenarios:



1. Existing coral reefs, represented by the bathymetry and coral cover published by CONABIO (2016).

2. Degraded coral reefs, represented by a 1-meter loss in reef crest height and reduced friction[3] of the reef surface.

Figure 9. Study area and coastal study unit.



3. Loss of friction in a reef is caused by the loss of live hard coral cover, resulting in a "smoother surface" where water forces could flow with less interruption or friction.

Figure 10. Details of bathymetry and seabed type for a section of Quintana Roo's coastline in Puerto Morelos. Maps enhanced by TNC based on information from the National Commission for the Conservation and Use of Biodiversity in Mexico (CONABIO).

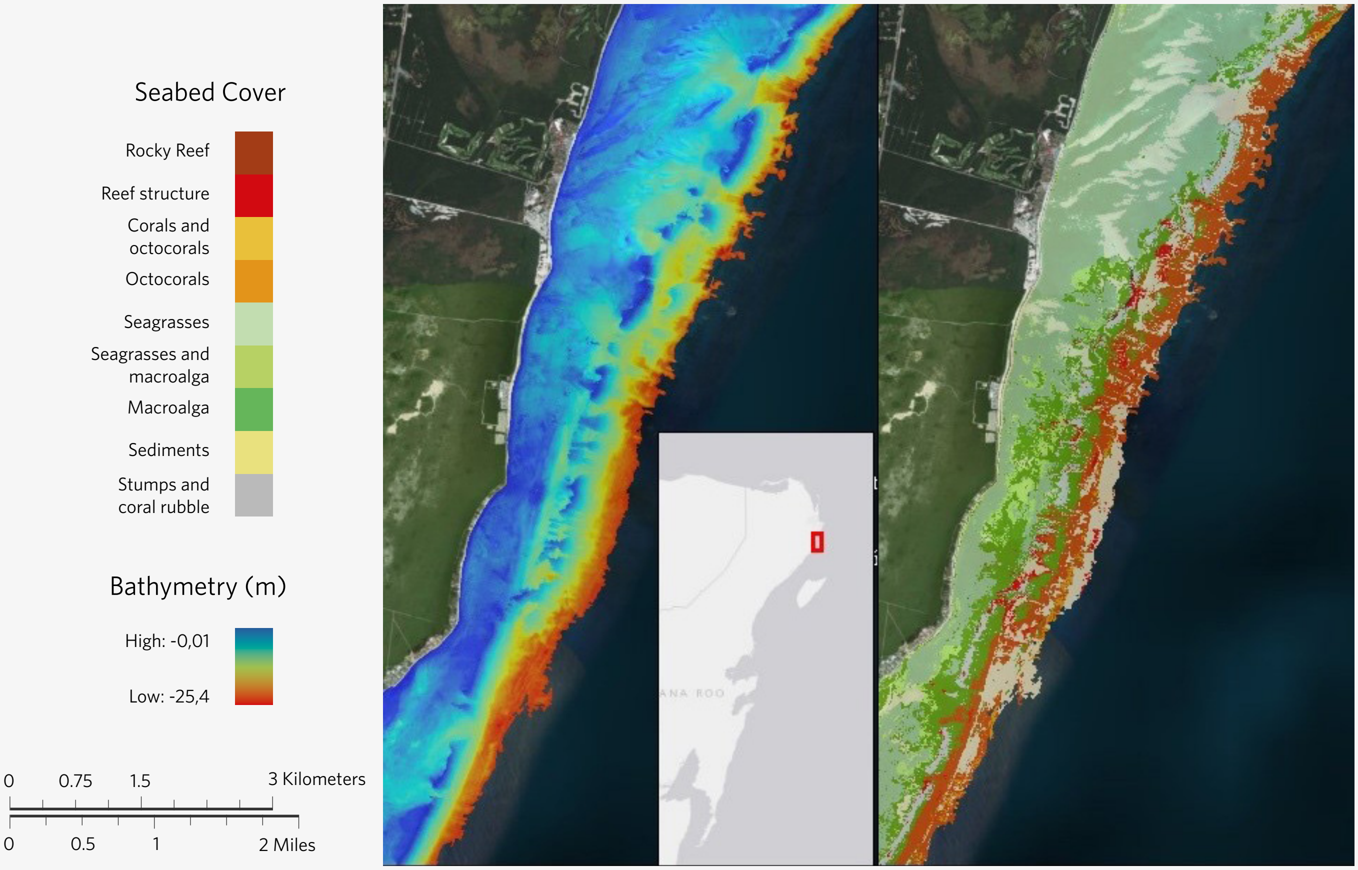


Figure 11

Figure 11 Example of the effect of reefs in coastal hydrodynamics or wave flow, in Puerto Morelos. (Photo from Google Earth)

Figure 12

Detail of the coastal transects used to model the effect of reefs on flooding.

Step 3. Calculation of losses

Losses are the estimates of people and buildings impacted by flooding, with hotels as a specific subset of impacted buildings.

This study used high-resolution population distribution (WorldPop) and the Mexico´s government census data on population to estimate how many people are exposed. To estimate affected people, we considered that all people who live in flooded areas are impacted, regardless of flood depth.

The study used GAR15 (UNDSIR, 2015) data to calculate the economic value of built-stock for residential, industrial, services and government stock exposed. The GAR15 provides a global exposure database with 5 kilometers spatial resolution. This information was downscaled to 100 m resolution using the WorldPop data and the local census data.

We built our own database on hotels using satellite imagery from Google Earth and digitized using ArcGIS. Hotel rooms and star ratings were identified through online database queries on different websites (e.g., TripAdvisor, Expedia, Booking.com, etc.) and interviews with local hotels.

This information was downscaled to 100 meters resolution using the WorldPop data and the local census data.

Economic losses to buildings (residential, commercial, industrial, and hotel stock) are calculated in each coastal transect for each storm by multiplying the value of the building by an expected percentage of damages. Vulnerability curves express the relationship between the flood depth and the percentage of value of the building that might be damaged. Each type of economic asset has its own specific vulnerability curve.

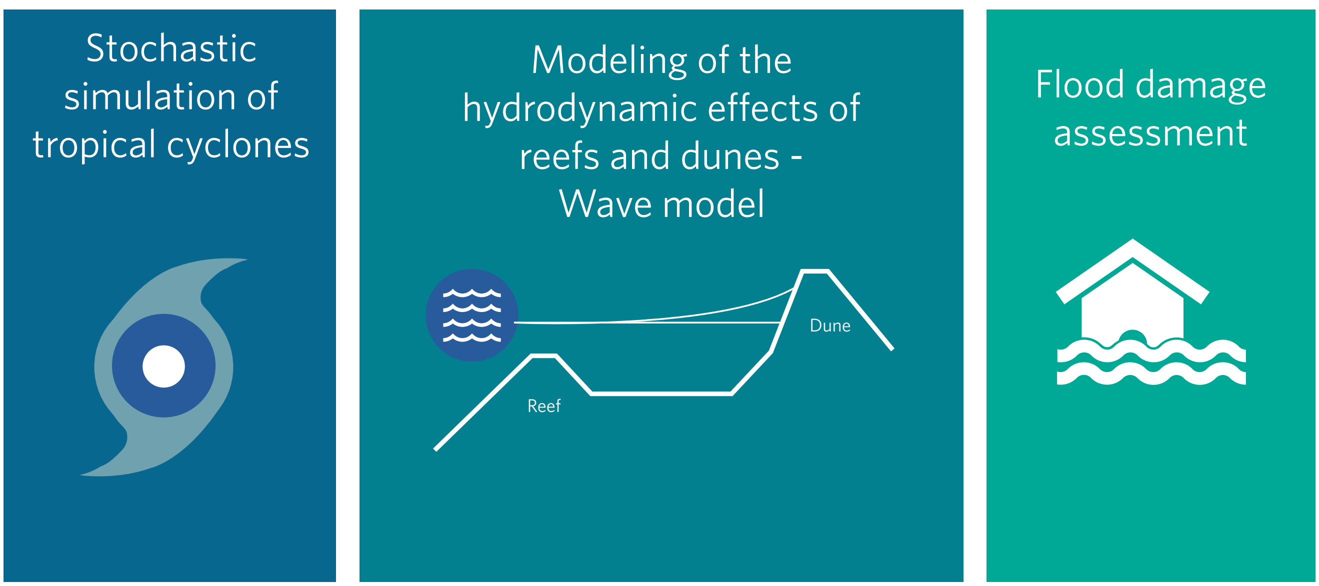
Degraded beach in Riviera MayaRiviera Maya © Fernando Secaira TNC

Step 4. Calculation of social and economic risk reduction benefits provided by reefs.

Risk is quantified by the number of people and monetary value of losses to buildings related to the frequency of flooding. Risk is described using an estimate of the annual average costs of flooding, known as Annualized Expected Damage (AED) associated with different storm return periods. Risk reduction benefits are the difference between coastal risks with and without reefs and are expressed in 2015 US Dollars.

Direct losses are damages caused to the infrastructure by flooding. Indirect losses are economic losses resulting from the consequences of damages to infrastructure, such as the interruption of business and the consequences on tourism. Estimates of indirect losses are based on data from previous natural disasters, compiled by Mexico's National Center for Prevention of Disasters (CENAPRED). The study calculated the ratio of indirect versus direct losses for hurricanes Dean, Wilma, and Emily and applied an average factor.

Figure 13. Elements used to conduct the analysis outlined in this report.



4

People and assets in coastal zone of Quintana Roo

4.1 People and assets at risk in the flood prone coastal zone

The analysis assessed people and assets in low-lying areas (below 20 m above mean sea level) within 5 km of the coast, which was designated the *'flood prone coastal zone'*. 72% of this coastline has adjacent coral reefs.

Out of Quintana Roo´s 1.5 million inhabitants, the *flood prone coastal zone* is home to:

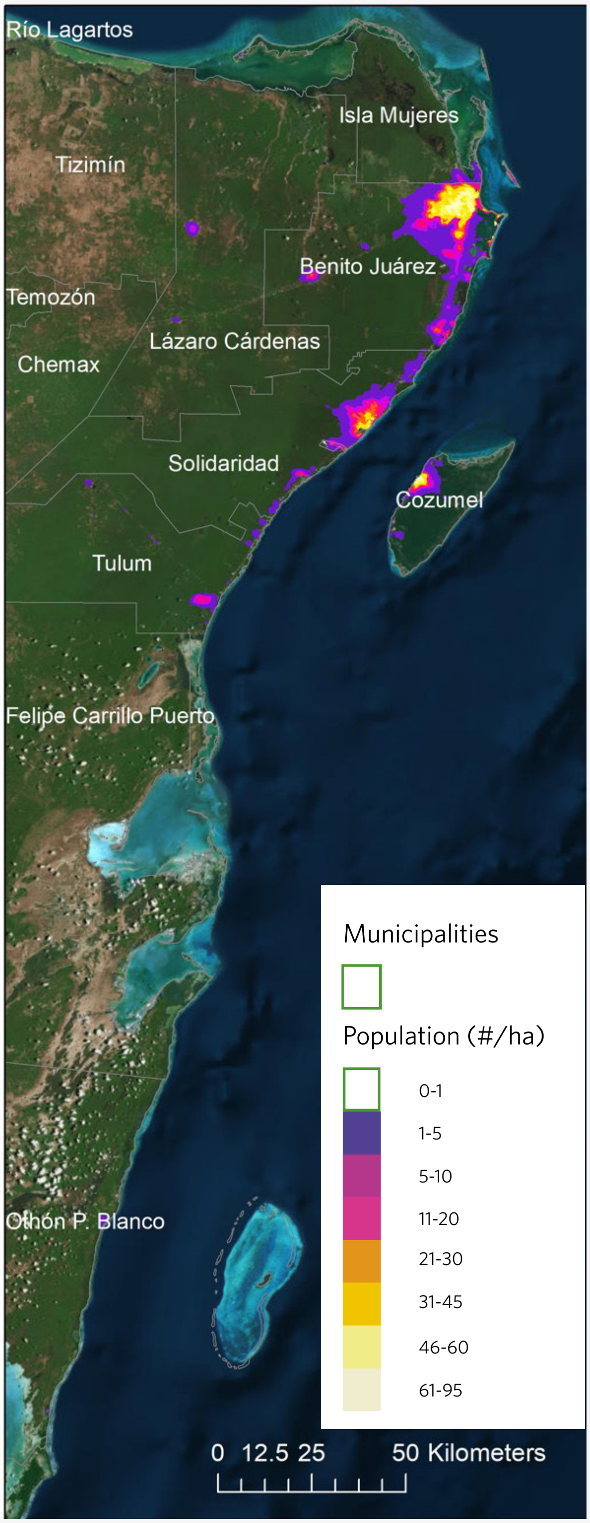
- ~307,000 people, of which ~105,800 live adjacent to reefs.
- USD 3.38 billion in built-stock, of which USD 900 million (26%) are adjacent to reefs.
- 959 hotels with a footprint of 1.5 million square meters, 63% of which are adjacent to reefs.

Table 1. People and stock exposed in the *flood prone coastal zone* (defined as being within 5 km of the coastline and below 20 m above mean sea level).

Type of Exposure	People and stock in the *flood prone coastal zone*	People and stock adjacent to reefs	Percentage of people and stock adjacent to reefs
Population (#)	307,640	105,800	34%
Residential built-stock (USD million)	1,737.4	518.0	30%
Industrial built-stock (USD million)	588.4	127.4	22%
Commercial built-stock (USD million)	1,058.2	223.1	21%
All built-stock (USD million)	3,384.00	868.50	26%
Hotels (million square meters)	1.529	0.967	63%

Figure 14. Areas of reef and no reef along the Mexican Caribbean.

Figure 15. Population distribution and density per hectare along the Mexican Caribbean.



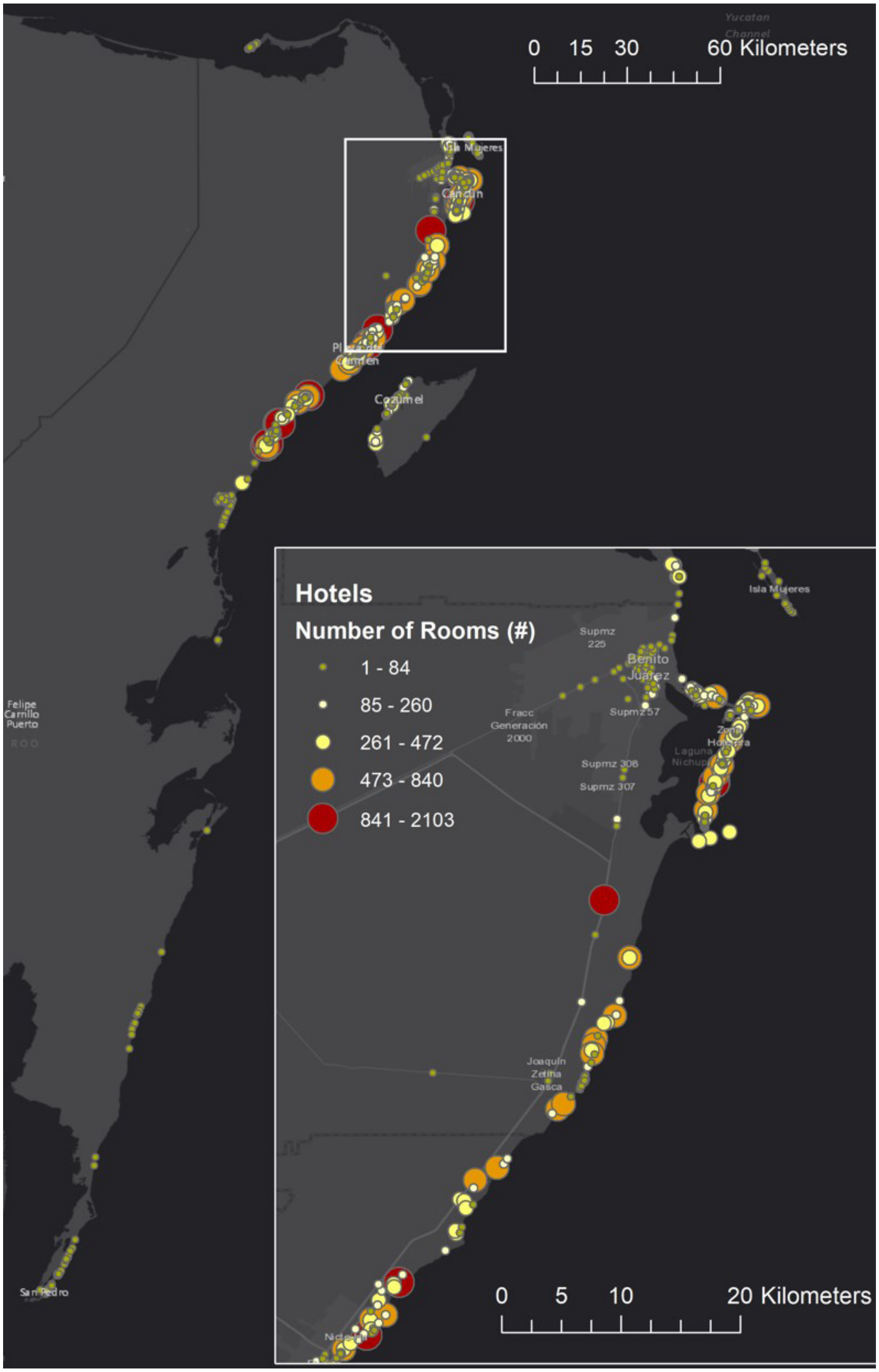


Figure 16. Hotel distribution and rooms in the Mexican Caribbean.

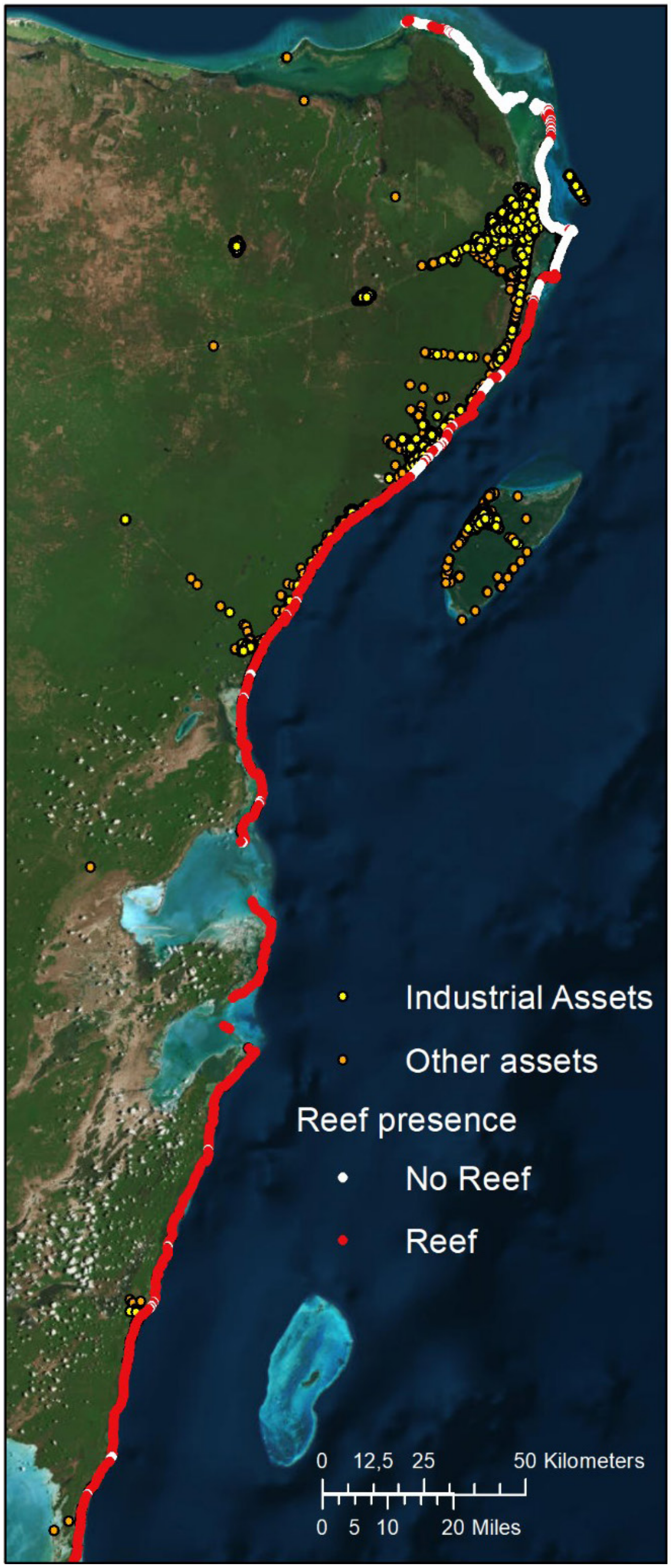


Figure 17. Distribution of built-stock and reef in the Mexican Caribbean.

5

Risk reduction benefits of the Mesoamerican Reef in the Mexican Caribbean

This section details the risk reduction benefits to people, built-stock, and hotels provided by reefs in the Mexican Caribbean. Each subsection includes estimates for:

- Damages with current reef (baseline risk);
- Damages with degraded reef (1 m loss of reef crest);
- Benefits or avoided damages.

The estimates are presented for storm return periods from 10 to 500 years, as well as on an annual basis.

5.1 Coastal protection benefits to people

People in the study area:

307,640

People in areas adjacent to/protected by reefs:

105,800

Benefits for sections with reefs (see Table 2):

Annualized number of people impacted would increase from **13,3093 to 17,679 per year.**

During a 1-in-100-year storm, **1 in every 9 people** is protected by reefs.

Annualized number of people protected is **4.3% of the 105,800** people in the flood prone coastal zone.

During a 1-in-25-year storm, **1 in every 20 people** is protected by reefs.

The annualized number of people impacted would increase by **35.3% if reefs are degraded.**

Figure 18. Annualized number of people affected by hurricanes. The dark blue represents the number of people that benefit from the protection provided by reefs.

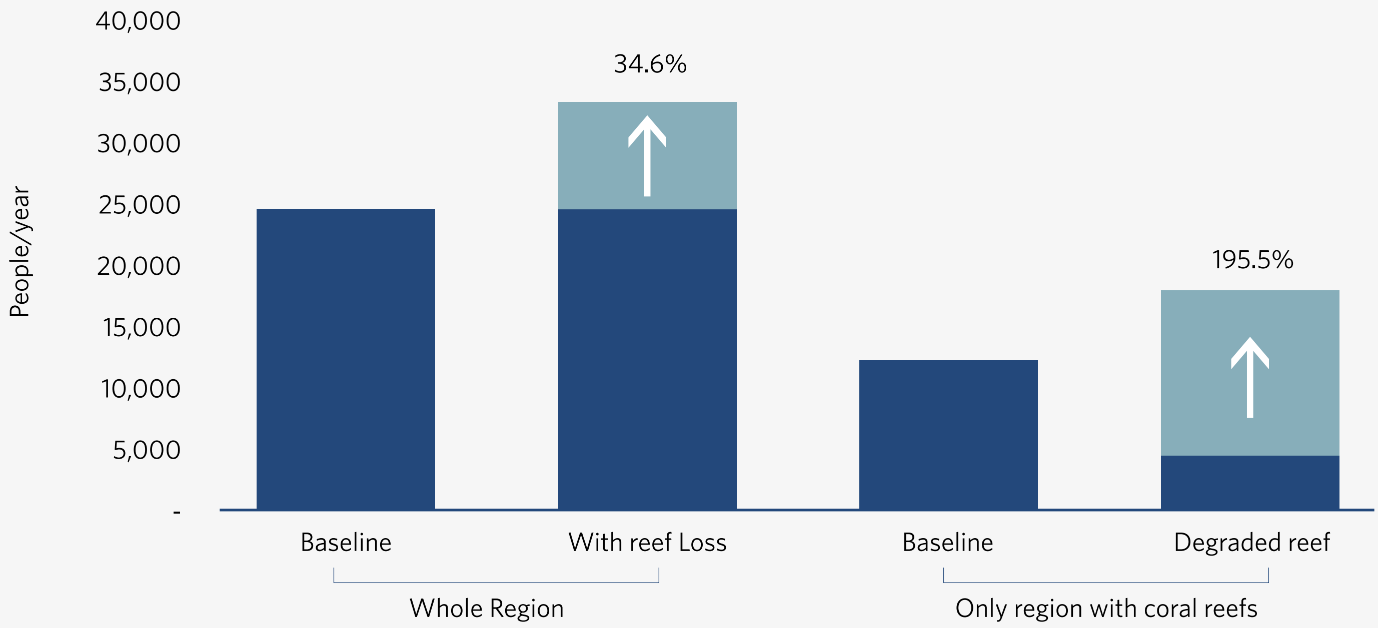
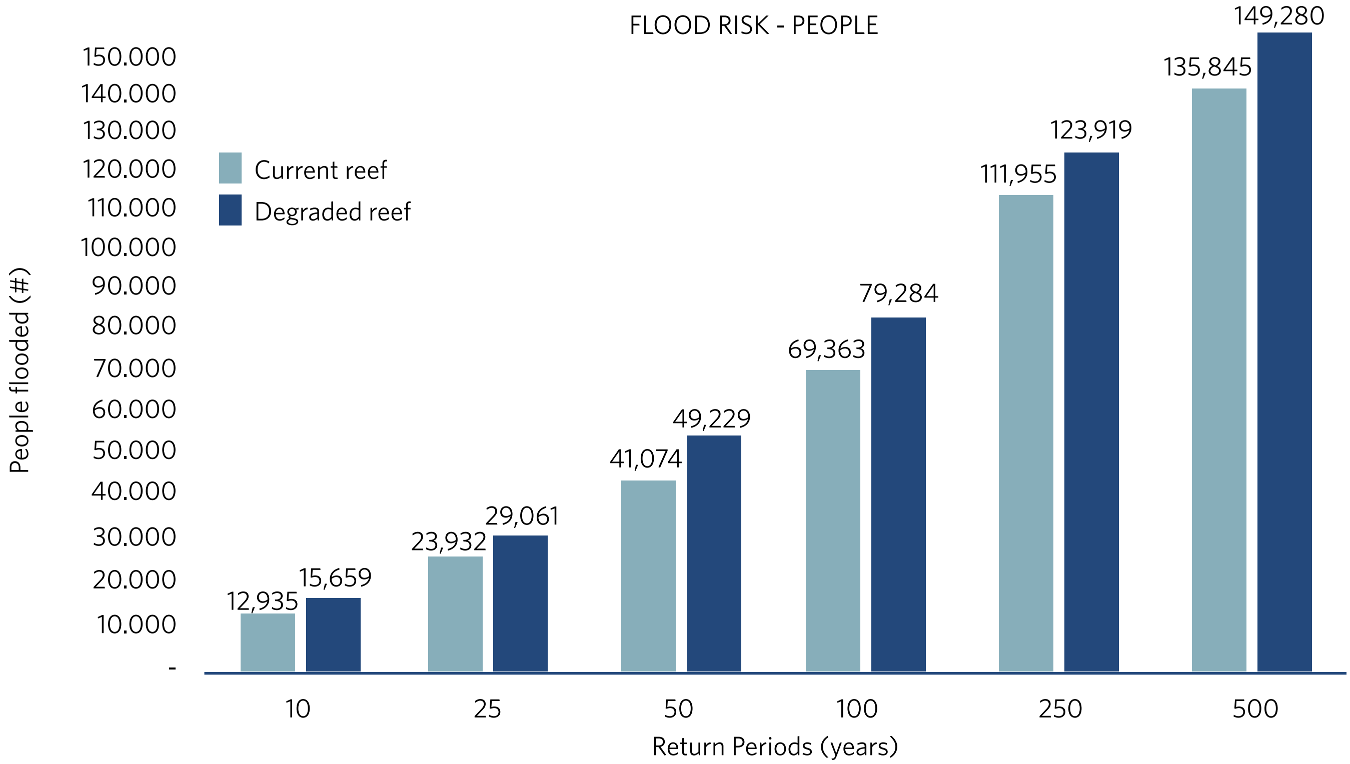


Table 2. People benefitting from flood protection provided by reefs. Annual Expected Damage is calculated as the probability of each storm and the associated losses. Values are expressed in number and percentage of people.

	Annual Expected Damage	Storm Return Period					
		10 years	25 years	50 years	100 years	250 years	500 years
People impacted with current reef condition (baseline risk)	13,093	12,935	23,932	41,074	69,363	111,955	135,845
People impacted with degraded reef	17,679	15,659	29,061	49,229	79,284	123,919	149,280
People benefited	4,586	2,677	5,140	6,941	8,796	10,784	13,478
Percentage of the benefit compared to baseline risk	35.03%	20.70%	21.48%	16.90%	12.68%	9.63%	9.92%
Population living behind reefs: 105,800							
Increase in risk compared to the total population	4.3%	2.5%	4.9%	6.6%	8.3%	10.2%	12.7%

Figure 19. People impacted by floods. The bars represent the people affected by flooding with current reefs and with degraded reefs. The difference between the bars represents the people who benefited from the reef. Values are expressed in terms of the number of people impacted by flooding. The total number of people living in coastal areas adjacent to reefs is 105,800.



5.2 Coastal protection benefits to built-stock

Value of built-stock in the study area:

USD 3,38 billion.

Value of built-stock in areas adjacent to/protected by reefs:

USD 858 million.

Expected annual losses would almost triple, increasing from

USD 9.2 million

with current reefs to USD 25.5 million with degraded reefs, a

178% increase.

Losses during a

1-in-100-year

storm would almost double if reefs degrade, increasing from **USD 136** million to USD 237 million. The avoided losses are equivalent to 11.6% of the value of all built-stock.

Losses during

1-in-250

and 500-year storms would increase by 56% anf 57.5% if reefs degrade.

Avoided losses from a

1-in-500 years

storm would be USD 172 million, 13 times higher than during more frequent storms (1-in-10 years).

The percentage of the avoided losses compared to the baseline is lower than other storms because the damages are far greater.

Figure 20. Annualized expected losses in built-stock for the region and for the area with reefs. The dark blue sections represent the avoided losses in built-stock due to the reef.

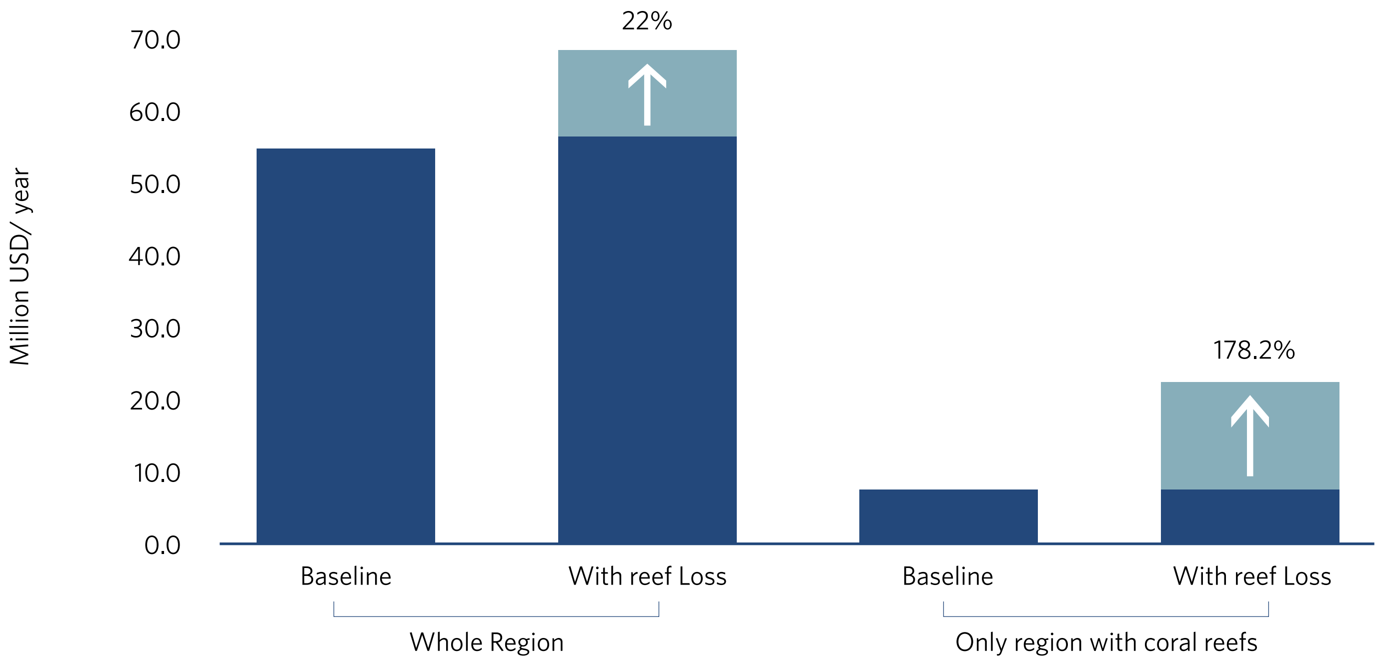
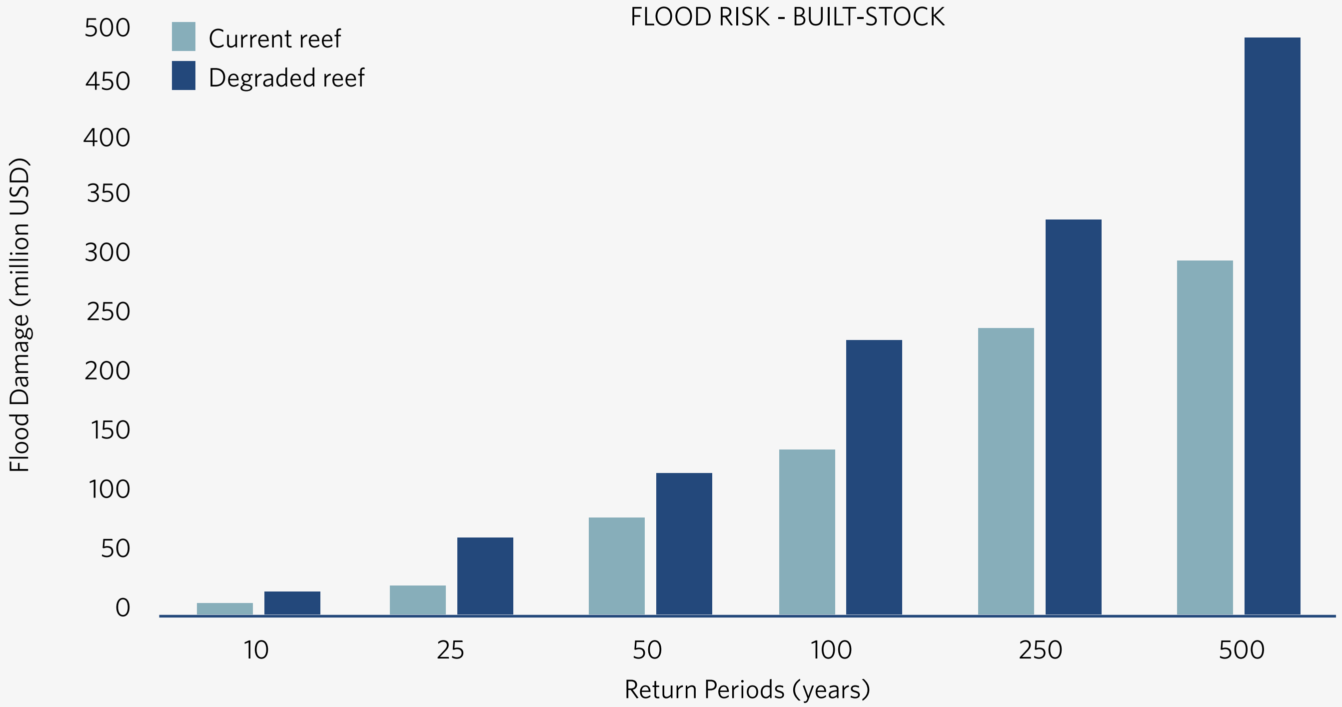


Table 3. Avoided damages to built-stock adjacent to and protected by coral reefs. Values are expressed in million USD.

Built capital (million USD) protected in sections with reefs	Annual Expected Damage	Storm Return Period					
		10 years	25 years	50 years	100 years	250 years	500 years
Damage with current reef (baseline risk)	9.2	13.7	29.3	62.1	136.2	233.4	298.9
Damage with degraded reef	25.5	26.9	62.1	118.8	237.0	364.1	470.6
Benefits or avoided damages	16.3	13.2	32.8	56.8	100.7	130.7	171.7
Percentage of the benefit compared to baseline risk	178.2%	96.9%	111.7%	91.4%	74.0%	56.0%	57.5%
Built capital behind reefs: USD 858 million							
Percentage of the benefit compared to the built-stock.	1.9%	1.5%	3.8%	6.5%	11.6%	15.1%	19.8%

Figure 21. Value of damages to built-stock. The bars represent the losses caused by flooding to built-stock with current reefs and with degraded reef. The difference between the bars represents the losses avoided due to the reef. Values are expressed in million USD. The total value of built-stock in areas adjacent to reef is USD 858 million.



5.3 Coastal protection benefits to hotels

Value of hotels in the study area:

USD 1.5 billion.

Value of hotels adjacent to/protected by reefs:

USD 957 million.

Expected annual losses to hotels would increase from

USD 12 million

to USD 32.8 million,

a 173% increase

if reefs degrade.

Losses during a

1-in-25-year

storm would increase from USD 31 million to USD 75 million, a 142% increase, with similar increases

(125% and 135%)

for 1-in-10 and 50-year storms, respectively.

The value of the avoided losses increases significantly with

1-in-500 storms

the losses would increase by USD 431.5 million, a 60% increase.

Avoided losses from a

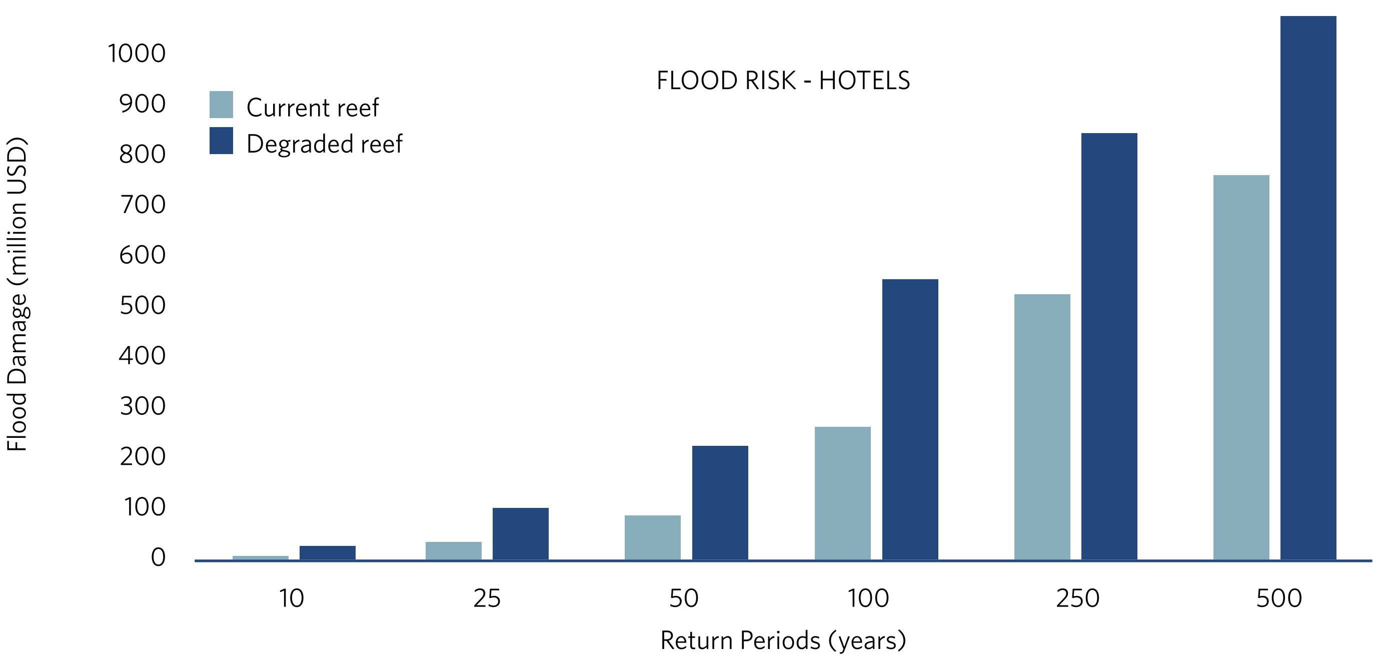
1-in-500-year

storm represent 50% of the value of all hotels, a very significant benefit.

Table 4. Avoided losses to hotels protected by reefs. Annual Expected Damage is calculated as the probability of each storm and the associated losses. Values are expressed in million USD.

Hotels (million USD) protected in sections with reefs	Annual Expected Damage	Storm Return Period					
		10 years	25 years	50 years	100 years	250 years	500 years
Damage with current reef (baseline risk)	12.0	16.8	41.9	99.6	287.8	506.0	719.2
Damage with degraded reef	32.8	37.5	100.3	230.1	550.4	838.1	1150.7
Benefits or avoided damages	20.8	20.8	58.4	130.5	262.6	332.1	431.5
Percentage of the benefit compared to baseline risk	173.3%	123.8%	139.2%	131.0%	91.2%	65.6%	60.0%
Value of hotels behind reefs: USD 957 million							
Percentage of the benefit compared to the value of hotels.	2.4%	2.4%	6.7%	15.0%	30.2%	38.2%	49.7%

Figure 22. Avoided losses to hotels protected by coral reefs. The bars represent the losses caused by flooding to hotels with current reefs and with degraded reefs. The difference between the bars represents the avoided losses provided by the reefs. Values are expressed in million USD. The value of all hotels is USD 957 million.



5.4 Spatial distribution of benefits

Annualized expected benefits for people (Figure 23), fo built-stock (Figure 24) and for hotels in each transects spaced 200-m along the coastline can be observed spatially. Benefits are provided where there are reefs; benefits are concentrated where people live and infrastructure is more developed.

Figure 23. Spatial distribution of annual expected benefits (AEB) in built-stock from flood protection provided by the Mesoamerican Reef in Quintana Roo in million USD.

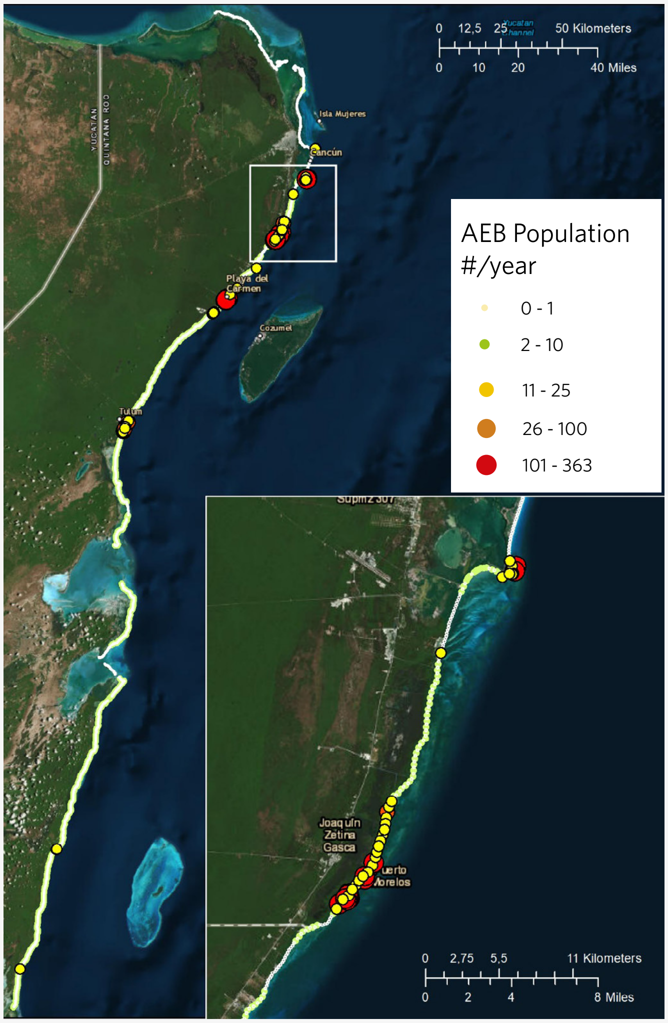
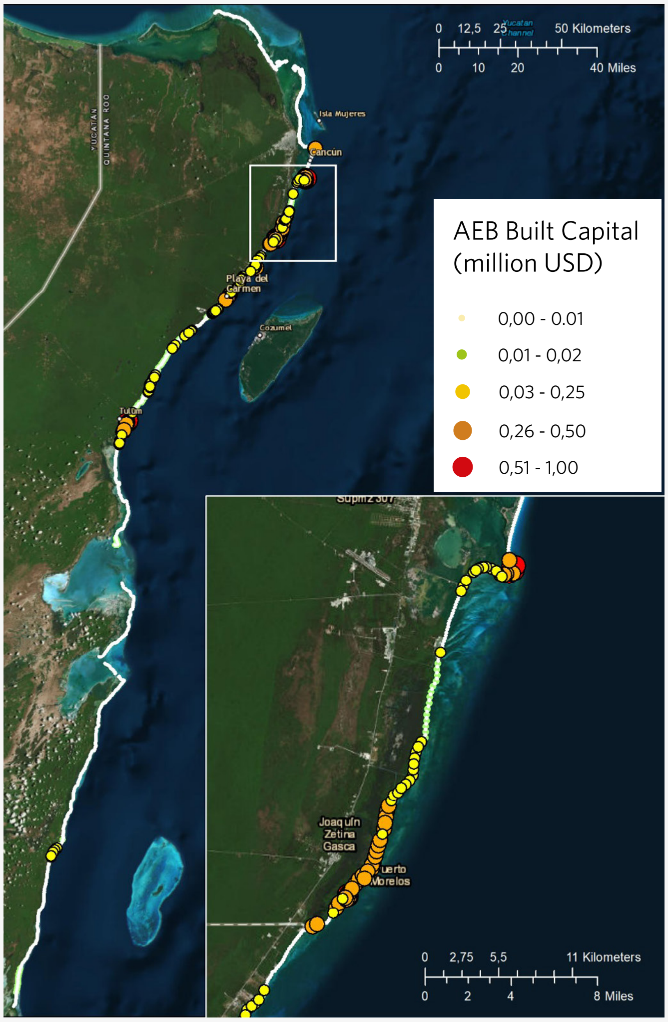


Figure 24. Spatial distribution of expected benefits in built-stock from flood protection provided by the Mesoamerican Reef in Quintana Roo for a 1-in-100-year storm in million USD.



5.5 Risk reduction benefits of coastal dunes

Dunes line the entire coast in the study area. The risk benefits they provide were calculated by including the dune height in the flood model when running Xbeach.

To estimate the difference in losses with dunes and without dunes, flooding with reefs and with dunes were considered as the baseline scenario. Flooding occurs when the total water level exceeds the dune height.

Because risk reduction benefits in sections with reefs are different from sections without reefs, results are presented in those categories.

> Flooding occurs when the total water level exceeds the dune height.

However, it is important to note that results for the dunes are *indicative*, as dune heights were estimated from satellite images since more robust data was not available.

Highlights:

The expected annual risk reduction benefits from dunes are estimated at

USD 16.7 million.

Risk reduction is more significant in sections without reefs

(USD 12 million)

than in sections with reefs (USD 4.7 million).

Dunes provide critical protection from more frequent storms. Dune reduces risk by

63%, 44.7% and 42.3%

for 1-in-10, 1-in-25 and 1-in-50-year storms, respectively.

Table 5. Avoided damages to built-stock protected by dunes. Values in million USD.

Damages to built-stock (million USD)	Annual Expected Damage	Storm Return Period					
		10 years	25 years	50 years	100 years	250 years	500 years
Study area							
Damages with reefs and dunes	55.5	43.4	110.3	220.6	621.6	1198.0	1541.1
Damages with reefs, but without dunes	72.2	70.7	159.6	314.0	636.4	1207.0	1550.3
Avoided damages by dunes	16.7	27.3	49.3	93.4	14.8	9.0	9.2
Percentage of increase in damages	30.0%	63.0%	44.7%	42.3%	2.4%	0.8%	0.6%
Only transects with reefs							
Damages with reefs and dunes	4.6	3.8	13.9	43.3	125.8	230.6	295.9
Damages with reefs, but without dunes	9.3	13.9	30.1	63.3	138.9	240.5	303.8
Avoided damages by dunes	4.7	10.1	16.2	20.0	13.1	9.9	7.9
Percentage of benefit over present risk	101.3%	264.1%	116.8%	46.2%	10.4%	4.3%	2.7%
Only transects without reefs							
Damages with dunes	50.9	39.6	96.4	177.3	495.8	967.4	1245.2
Damages without dunes	62.9	56.8	129.5	250.7	497.5	966.5	1246.5
Avoided damages by dunes	12	17.2	33.1	73.4	1.7	0	1.3
Percentage of benefit over present risk	24%	43%	34%	41%	0%	0%	0%

6
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