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Samuel Battut, Tony Rey, Raphaël Cécé, Didier Bernard, Yann Krien. Responses and adjustments of the coastal systems of Dominica (Lesser Antilles) when faced with an extreme event: Hurricane Maria (September 2017). *Natural Hazards*, 2022, 116 (1), pp.151-191. 10.1007/s11069-022-05668-2 . hal-03831607

HAL Id: hal-03831607

<https://hal.science/hal-03831607>

Submitted on 12 Mar 2024

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Responses and adjustments of the coastal systems of Dominica (Lesser Antilles) when faced with an extreme event: Hurricane Maria (September 2017)

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Research Article

Keywords: Hurricane Maria, Dominica, coastal changes, damage, vulnerability

Posted Date: March 14th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1183825/v1>

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Abstract

Dominica was hit hard by Hurricane Maria, a Category 5 storm when it passed over the island on September 18, 2017. This study aims to characterise the dynamics associated with this extreme event and their consequences in the medium term on the morphology and the coastal structures of this Caribbean island nation. Based on a multi-site approach (9 sites), this study uses varied data (satellite and aerial images, databases, reports, numerical modelling) and the validation thereof via qualitative observations and topo-morphological surveys carried out in the field 18 months after the hurricane. The high-resolution modelling of the hydrometeorological conditions during the hurricane, the monitoring of the changes in the shoreline, and the field observations brought to light the prevalence of fluvio-sedimentary hazards (torrential flooding, ground movements) over marine hazards (marine flooding, storm swell) in the modification of the coastal landscapes. Phenomena of massive sediment discharge caused considerable damage to the buildings located in low-lying areas and flood plains and to road infrastructure, which hindered access to certain sectors of the island in the post-storm phase for a significant period of time. The more-limited damage of marine origin was exacerbated by the artificialisation of the coast and the establishment of a permanent shoreline. We demonstrate that the impact model for Hurricane Maria for the coastal areas of Dominica is the result of a combination of natural factors with a particular exposure and vulnerability of coastal populations and structures to hydrometeorological risks.

1. Introduction

The 2017 hurricane season in the North Atlantic basin, marked by 17 events, including 6 major hurricanes (Category 3 or higher on the Saffir-Simpson scale), was one of the most active and most costly in terms of damage ever recorded. The total economic losses are estimated at more than 200 billion USD according to reinsurance company Munich Re (2018). There were over 3,000 deaths, and the number of people affected by storm events in the region in 2017 is estimated at over 11 million (CRED 2019). Early feedback revealed strong disparities in the levels of vulnerability among the Caribbean islands (Nicolas et al. 2018). This variability can be observed through the amount of damage (Rey et al. 2019) and the recovery capacity of populations in the post-storm period (Defossez and Gherardi 2020; Moatty et al. 2020). The areas most affected by hurricanes in 2017 include a large number of Caribbean islands, such as Puerto Rico (Meléndez and Hinojosa 2017), Saint-Martin (Duvat et al. 2019), Saint-Barthélemy (Pillet et al. 2019; Rey et al. 2019) and Dominica (Heidarzadeh et al. 2018).

Small tropical islands are often designated as being particularly exposed and vulnerable to a large variety of natural hazards (Méheux et al. 2006), in particular to high-energy events such as tropical storms. More specifically, the Caribbean Small Island Developing States (SIDS), 29 in number according to the UN classification (United Nations 2011), are characterised by vulnerabilities related to the physical particularities of small tropical islands: active storm basin, small size, isolation and territorial fragmentation, ecosystem sensitivity, and limited resources (Briguglio 1995; Nurse et al. 2014; Shultz et al. 2016). In addition to these physical constraints, there are social, economic, and cultural vulnerabilities and the weighty heritage of the colonial history of the Caribbean. This includes poverty and social inequality, (Bowen 2007), structural dependencies (Girvan 1997, 2012), high debt (Robinson 2014), and production specialisations that are particularly sensitive to natural disasters, such as export agriculture (Mohan 2016) and mass tourism (Granvorka and Strobl 2010). Outside pressure like colonisation and global changes have and continue to exercise a major influence on the vulnerability of these territories, which saw the birth of the globalisation of exchanges (Lewis and Maslin 2015) and which must now face the threat of climate change (IPCC 2013).

The observed and predicted increase in the intensity of tropical storms (Webster et al. 2005), in particular in the intertropical zone of the North Atlantic basin (Murakami et al. 2018), casts doubt on the response capacity of the SIDS in the face of extreme meteorological events. In meteorology, an extreme event is defined by its frequency of occurrence, expressed in return periods or in quantiles. From the point of view of wind speed, an abnormally intense storm covers values in the highest 10% (9th decile) of all the values observed. The most frequent phenomena, with a low or medium intensity, are thus distinguished from the phenomena that are rarer and have a higher intensity. The former tends to weaken territories by causing recurrent economic and human losses (Marulanda et al. 2011; Gaillard et al. 2014), while the latter can radically and suddenly transform territories by the scope and the level of the damage done. But the magnitude of a "natural" disaster, although it may vary according to the intensity of the hazards, is first and foremost determined by the vulnerability of the social systems that are faced with it (Quarantelli 1998; Wisner et al. 2012). While major disasters attract more attention from the public and from decisionmakers, eliciting international aid, they are an extension of the faults and problems of daily life, which are the source of small disasters that usually affect the most underprivileged first (Gaillard et al. 2014). While we avoid adopting a fatalistic or deterministic vision of these territories (Farbotko 2010; Kelman 2018), recent events (like the 2017 Hurricane Season) and future risks highlight the importance of improving the comprehension of the mechanisms of response of the SIDS to extreme meteorological events.

In 2017, 11 of the 29 Caribbean SIDS were affected by Category 5 storms (Shultz et al. 2019). On September 18 of that year, Hurricane Maria battered the island of Dominica, causing an amount of damage unprecedented in the island's history. The passage of the hurricane devastated this young nation of the Lesser Antilles, leading to the deaths of 64 people and total economic losses estimated at approximately 1.3 billion dollars (US), or 226% of the GDP for 2016 (Government of Dominica 2017). The storm affected the entirety of the population and added to the heavy toll of Tropical Storm Erika two years earlier, on August 27, 2015. Shortly after the hurricane, studies aiming to evaluate the consequences thereof were carried out on the initiative of the government (Government of Dominica 2017), NGOs and researchers (Heidarzadeh et al. 2018; Philogene Heron 2018; Hu and Smith 2018; Schaefer et al. 2020). However, these one-time studies do not all highlight the complexity of the spatial and temporal dynamics of the recovery of physical and human systems. This article thus presents feedback on the impact of Hurricane Maria on Dominica in the medium term. The analyses were carried out on the coast, where most of the population and strategic resources of the island are concentrated. The high-resolution numerical modelling of the atmospheric and hydrodynamic characteristics of the hurricane (part 4.1, 4.2), supplemented by the monitoring of the position of the shoreline by photo interpretation (4.3, 4.4) and confirmed by on-site observations (4.5), allowed us to document with precision and thoroughness the specific impact model of Hurricane Maria on highly exposed low-lying coasts. Beyond the morpho-sedimentary response of the coastal cells, we also analysed the damage to coastal structures (4.6.1) and the recovery and adaptation capacities of the territory in terms of road access (4.6.2).

2. Context

2.1. Physical features of Dominica

Dominica is a small island state located in the heart of the arc of the Lesser Antilles, between the Caribbean Sea and the Atlantic Ocean (Fig. 1). With an area of 754 km², its shape is elongated along a north-south axis (approximately 50 km long and 25 km at its widest); this is evoked in its indigenous Kalinago name *Wai'tu kubuli*, which means "tall is her body". Located in the recent volcanic arc of the Lesser Antilles, Dominica is composed of a chain of volcanoes, 7 of which are potentially active, created during the Pleistocene, making it the most mountainous island of the Lesser Antilles (Lindsay et al. 2003). Morne Diablotins, the tallest, culminates at an altitude of 1,447 m. Dominica's highly broken relief traps the precipitation of the masses of hot and humid air driven by the trade winds coming from the Atlantic. The island consequently enjoys a humid tropical climate, although there are significant variations in precipitation over the entire territory. The eastern, windward coast receives on average 500 cm of rain per year; the mountainous interior, which is the most humid, receives 900 cm; and the western, leeward coast receives 180 cm on average (Allen 2017). This abundance of precipitation and the roughness of the terrain led to the creation of a dense hydrographic network composed of over 350 streams (Lindsay et al. 2005). In the hurricane season or during storms, the streams can reach very high peak flows, sometimes amplified by the collapse of dams produced by ground movements (Ogden 2016). Bravard et al. (2001) reported a peak flow that can reach over 650 m³/s for the Layou River, located in the western central part of the island. Ogden (2016) estimated that the indirect peak flows of 16 streams could have reached 163 to 2,876 m³/s during the passage of Tropical Storm Erika (August 2015). The substrates, composed especially of thick, loosely consolidated pyroclastic deposits (Bravard et al. 2001), and covered by fine, permeable soil (Rouse et al. 1986), make the slopes vulnerable to water erosion. More particularly, during intense and prolonged precipitation, as is the case during storm events, the saturation of the soil with water can trigger ground movements of large magnitude (Rouse 1990).

Fig. 1 Map of Dominica and location of study sites. Location of coral reefs and assemblages is modified from Steiner (2015). Map of land occupation from 2017 modified according to Hu and Smith (2018)

The coast of Dominica mainly consists of high rocky coastline, which represents almost 70% of the 148 km of coast, in particular on the northern and eastern facades (Fig. 1). Some narrow coastal plains are scattered around the contour of the island, where sand and pebble beaches make up 10% and 15% of the coastline, respectively. Only 5% of the coastline is artificialized, versus 9% in Guadeloupe (Roques et al. 2010) and 11% in Martinique (Lemoigne et al. 2013). Dominica is located in a microtidal context, and the magnitude of the tide is less than 1 metre. The tidal data of the IGN recorded on Marie-Galante (port of Grand-Bourg, 15°52'48.6"N 61°19'01.2"W), 30 km north of the island, indicates that the highest astronomical tide is 82 cm and the lowest astronomical tide is 15 cm. The average level is defined as 54 cm (with respect to the French hydrographic zero). While this information gives an indication of wave behaviour and variations in sea level, it should not be used to conceal the complexity of the conditions near the coast according to the various geomorphological contexts (bay beach, open beach, bathymetry, etc.). Because of the narrowness of the continental shelf (Fig. 1), mangrove development is limited to small areas located mainly in the northwest of the island (Godt 1990). Half of the few coral reefs are concentrated on the north coast of the island (Steiner 2015).

The island of Dominica is located both in one of the most dynamic storm basins (North Atlantic basin) in terms of cyclogenesis and in a particularly active storm corridor called the Main Development Region (Goldenberg and Shapiro 1996). Various historic sources were used to establish that a total of 178 storms and hurricanes have significantly affected Dominica between 1502 and 2018 (Barclay et al. 2019). For the period from 1950 to 2019, the International Best Track Archive for Climate Stewardship (IBTrACS) database of the National Oceanic and Atmospheric Administration (NOAA) has recorded 34 hurricane and storm trajectories with an eye that passed less than 100 km from the island, which represents on average one event every two years. Overall, the depressions and tropical storms, that is to say the events with a sustained wind speed of less than 118 km/h, are overrepresented, making up almost 75% of the total (Fig. 2). The last decade (2010-2019) saw the largest number of events (9) affecting Dominica. Characterised by a single Category 5 event, it came after 2 decades with few storms (2-4 events) and high-intensity events (at most Category 1).

Fig. 2 Number and intensity of depressions, tropical storms and hurricanes per decade between 1950 and 2019 with an eye that passed 100 km or less from Dominica. 1. Unnamed storm. 2. Tropical depression or storm (sustained winds of less than 118 km/h). 3. Category 1 hurricane (sustained winds between 119 and 153 km/h). 4. Category 2 hurricane (sustained winds between 154 and 177 km/h). 5. Category 3 hurricane (sustained winds between 178 and 210 km/h). 6. Category 4 hurricane (sustained winds between 211 and 251 km/h). 7. Category 5 hurricane (sustained winds of more than 251 km/h). The class of intensity for each storm depends on the wind speed reached at the point of the trajectory closest to the centroid of the island

2.2. Socioeconomic context of Dominica

Colonised in turn by France and Great Britain between the 16th and 19th centuries, Dominica gained its independence from the British Crown in 1978. A member of the Commonwealth, it still maintains diplomatic and commercial ties with the United Kingdom. The population of the island increased constantly starting from the middle of the 18th century and reached a maximum number of approximately 75,000 inhabitants at the beginning of the 1980s (Barclay et al. 2019). Today, the island is home to about 70,000 people, which represents one of the lowest population densities in the Antilles (96/km²). The population is mainly concentrated on the western shore of the island (leeward side), where the greatest densities are recorded, in particular in the capital Roseau (15,000 inhabitants) and around Portsmouth (3,600 inhabitants). The urbanisation is concentrated in the low-lying coastal and fluvial plains (Fig. 1), which are particularly exposed to hydrometeorological risks. The country is facing a difficult economic and social situation marked by a trade deficit and a high rate of debt. In 2006, 39% of the population was considered to be living in poverty (Ballini et al. 2009). The export agriculture inherited from colonisation continues to occupy a significant place in the national economy despite the decline of the banana industry since the 1980s; at that time, it employed 2/3 of the workforce. Since then, the country has undertaken a diversification of the agricultural production, but the banana remains the most-exported crop. Almost 30% of the surface of the island is occupied by crops (Fig. 1), for the most part as subsistence agriculture. In parallel, the tourism sector has been progressively developed on the island, and the number of arriving tourists increase from 60,000 in 1995 to almost 80,000 in 2016 (World bank 2021). Since Dominica does not enjoy

the same conditions favourable to mass tourism (accessibility, large housing capacity, sandy beaches) as many other islands of the Antilles (Weaver 1991), the government has opted for sustainable tourism centred on the landscapes, which have been preserved due to the low anthropic pressure. These two sectors (agriculture and tourism) are often designated as vulnerable to natural disasters. Storm episodes regularly destroy crops and damage tourism and transport infrastructure (Hammerton et al. 1984; Mohan 2017).

2.3. Characteristics, trajectory and dynamics of Hurricane Maria

The 2017 hurricane season, particularly active in the North Atlantic basin (Klotzbach et al. 2018), saw six major hurricanes (Category 3 or higher on the Saffir-Simpson scale), including two Category 5 hurricanes (Maria and Irma). Hurricane Maria was the seventh hurricane of the season. When it passed over Dominica, it reached Category 5, a level of intensity never before recorded on the island. It was one of the five hurricanes with an eye that passed over the island since 1950, along with Beryl in 2018, Marilyn in 1995, David in 1979 and Betsy in 1965. It was also the deadliest event of the 2017 season, with almost 3,000 victims (Kishore et al. 2018; Santos-Burgoa et al. 2018). Following a typical trajectory, Hurricane Maria formed off the coast of West Africa as a tropical wave and reached the stage of tropical depression on September 16 approximately 900 km to the east of Barbados (Fig. 3). A first tropical storm watch for Dominica was issued by the National Hurricane Center (NHC) of the NOAA on September 16 at 11:00 local time. Continuing its path to the west on September 17, the tropical storm intensified to become a hurricane. The watch became a hurricane watch on September 17 at 5:00, and the hurricane warning was issued the same day at 11:00. Very favourable meteorological conditions near Dominica (available masses of warm water, very low vertical shearing) allowed Maria to go from Category 1 to 5 in only 15 hours (Jury et al. 2019), just before its landfall in Dominica on the evening of September 18. This rapid intensification surprised the population and the local authorities, who were expecting a Category 2 hurricane, as initially predicted. The eye of the storm passed over the island along a southeast to northwest axis and continued westward, also passing over Puerto Rico, along the north coast of Hispaniola and the eastern part of the Bahamas before heading north and losing power 500 km off the coast of North Carolina (United States).

Fig. 3 Trajectory and characteristics of Hurricane Maria (16/09 - 02/10/2017) in the North Atlantic basin. Times are expressed in Coordinated Universal Time (UTC)

3. Methodology

3.1. Selection of study sites

In order to assess the impact of the hurricane and the post-storm recovery processes on the coast of Dominica, 9 study sites spread over the contour of the island were selected (Fig. 1) (i) according to their accessibility, (ii) according to the magnitude of the morphological modifications that occurred after the passage of the hurricane, detected via the observation of satellite images, and (iii) in such a way as to produce a sample of the Dominican coast sufficiently diverse and representative to highlight the variability of the effects of the hurricane according to the various morphological and anthropic coastal configurations (Table 1). 7 sites include pebble beaches and 4 are densely urbanised along the waterfront. Among the 9 sites, 4 are located on the west coast: Portsmouth Bay, also called Prince Rupert's Bay (Fig. 4a), Colihaut (Fig. 4b), Mahaut (Fig. 4e) and Scotts Head (Fig. 4h); 2 on the south coast: Grand Bay (Fig. 4i) and Fond Saint Jean (Fig. 4f); and 3 on the east coast: Number One Beach, also called Hampstead Beach (Fig. 4c), Pointe Mulâtre (Fig. 4g) and Petite Savanne (Fig. 4d). Most (6 sites) are located in the southern half of the island.

Fig. 4 Overview of the 9 study sites: Portsmouth Bay (a), Colihaut (b), Number One Beach (c), Petite Savanne Bay (d) Mahaut (e), Fond Saint Jean (f), Pointe Mulâtre (g), Scotts Head (h), Grand Bay (i). The location of the sites is indicated in Fig. 1. The white line indicates the extent of the coastline studied for the monitoring of the changes in the shoreline

The sites selected are located in well-drained catchment areas (average drainage density of 5.52 km/km²) with steep slopes (between 16.65 and 26.08% on average). The shape and the slope of the catchment areas result in short concentration times during floods. On average, the longitudinal slope of the main streams is equal to 12.12%. These factors are responsible for a high stream competence, which translates into a significant mobilisation of coarse material during floods.

Table 1 General characteristics of the selected study sites. Population data is from the 2011 census (Government of Dominica 2011). Information on the location of the coral reefs and assemblages are from Steiner (2015)

3.2 High-resolution modelling of the hydrometeorological characteristics of the hurricane

The use of numerical models reinforced the accuracy of reconstruction of the spatial variations in intensity of the hurricane-related hazards while compensating for the lack of observational data and the faults in measurement devices (tide and rain gauges) during the passage of Hurricane Maria. The results made it possible to establish the relationship between the intensity of the storm phenomena and their location, the morphological impact observed on the ground, and the nature of the damage to coastal structures.

3.2.1 Hurricane winds and rain

When Hurricane Maria made landfall in Dominica, the maximum sustained winds were estimated at 270 km/h (Pasch et al. 2019). The heavy rainfall caused major river flooding in the mountainous island. Due to the lack of available observational data, the local meteorological effects of Hurricane Maria were examined via numerical modelling. The WRF-ARW atmospheric model (Skamarock et al. 2008) was used with large eddy simulation to achieve a very fine scale of 90 m over the entire island. The main initialisation, dynamical and physics parameterizations selected here showed a good ability to reproduce the landfall effects of Hurricane Irma (2017) over Saint-Martin and Saint-Barthélemy (Cécé et al. 2021). Due to computational instabilities, the 1.5-order turbulence kinetic energy (TKE) linear eddy-viscosity SFS stress model (Lilly 1967) was chosen instead of the more realistic nonlinear backscatter and anisotropy (NBA)

SFS stress model (Mirocha et al. 2010). Based on the conclusions of Cécé et al. (2021), the use of the TKE SFS stress model could lead to a slight underestimation of peak surface gusts.

3.2.2 Storm swell

To get a better understanding of the hydrodynamic conditions during Hurricane Maria, we reproduced sea states and storm surges using SCHISM-WWM, a state-of-the-art wave-current coupled numerical model (Zhang et al. 2016). Global bathymetric data (GEBCO) for the deep ocean was supplemented by very-high-resolution shallow-water and inland lidar data. The model is forced by tide, as well as wind and pressure fields computed using parametric formulas (E11H80, Krien et al. 2018) applied to NHC best-track data. The computational domain extends from 67.7°W to 45°W and from 9.4°N to 21.7°N, with resolutions spanning from 10 km in deep waters to 50 m at the coast.

3.3. Evaluation of the changes in shoreline caused by the passage of the hurricane

The changes in position of the shoreline due to the passage of the hurricane were estimated via the acquisition and integration of aerial and satellite images from various sources (Table 2) into GIS. All were high-resolution images, with a pixel size varying from 4 to 50 cm. For each study site, a before-storm reference image and a post-storm image as close as possible to the event were selected. The most recent possible image was added in order to estimate the post-storm regeneration processes. This selection was carried out according to the availability of the images and their readability, in particular the amount of cloud cover, which sometimes masked all or part of the study site. For this reason, and because of the significant distance between the various sites, the date and the source of the images differ for most of the sectors studied. The images selected were then georeferenced in Qgis 3.10 using the WGS 1984 UTM zone 20N (EPSG: 32620) coordinate system. The swash limit, or instantaneous position of the shoreline, defined by the limit between the dry and wet sediments, was used to digitise the position of the shorelines on each image. This reference is routinely used in a microtidal context (Boak and Turner 2005; Faye 2010; Gaillot and Chaverot 2001; Lemoigne et al. 2013; Robin 2002). The changes in position of the digitised shorelines were calculated in Arcmap 6.0 using the Digital Shoreline Analysis System (DSAS) extension, version 5.0. Transects spaced 10 metres apart were used to quantify the advance or retreat of the shoreline relative to a reference line generated parallel to the shore. The program calculates the distance between the oldest and youngest shoreline, called Net Shoreline Movement (NSM). In addition to the transects, the change in the shoreline was also quantified in terms of surface area of change. For this, the surfaces between the various lines were polygonised in Qgis so as to calculate their surface areas.

Table 2 Characteristics of the images used for the monitoring of the change in the position of the shoreline

3.4. Evaluation of the uncertainty related to the change in the shoreline

Despite the care taken by the operator during the digitisation of the shoreline on the basis of aerial and satellite images, this operation is subject to potential errors that can affect the reliability of the results. This uncertainty, which has already been the subject of several studies (Anders and Byrnes 1991; Crowell et al. 1991; Thieler et al. 2009; Thieler and Danforth 1994; Moore 2000), is related to the quality of the images, their processing, and the effects of seasonal changes or of the tide. In Dominica, the position of the shoreline is not greatly influenced by variations in sea level since the average amplitude of the tide is less than 1 metre (Steiner 2015), and it is not affected by seasonal variations. Consequently, these indicators were not integrated into the estimation of the uncertainty. However, the highly uneven topography of the island, including in the coastal areas, tends to induce deformations and affects the quality of the aerial and satellite images. Following previous studies (Duvat et al. 2017; Juigner et al. 2013; Moussaid et al. 2015), three indicators were selected: pixel error (E_p), correction error (E_r), and digitisation error (E_d). Each of these errors was calculated separately for each study site (Table 3). E_p corresponds to the resolution of the image, or the pixel size. It is equal to the average of the resolution of the images. E_r relates to the differences in positioning that remain between the various images after their georeferencing via control points (landmarks). It was calculated by placing 5 points on random landmarks close to the shore for each georeferenced image. The differences between the points of the various images were calculated using the distance-measuring tool in Qgis. E_r is equal to the average of the mean differences recorded for these 5 points. E_d represents the errors related to the subjectivity of the operator when they determine and trace the position of the shoreline. It was calculated by repeating the digitisation operation 3 times for each image and then calculating the maximum distance between the 3 lines. E_d is equal to the average of the maximum distances recorded for the three images. The overall error in position of the shoreline (E_{g1}) is calculated by using the equation: $E_{g1} = \sqrt{E_p^2 + E_r^2 + E_d^2}$. The margin of uncertainty for the position of the shoreline (E_{g1}) varies between ≤ 2.44 (Colihaut) and ≤ 4.79 m (Petite Savanne). On average, $E_{g1} \leq 3.74$ m. The transects with values that fall within this margin of uncertainty are considered to be stable since it is impossible to define with certainty the trend in the change thereof. For example, for Colihaut (Table 3), the values of NSM ≤ -2.44 m indicate a tendency to erosion, those between -2.44 and $+2.44$ m indicate stability, and those ≥ 2.44 m indicate an advancing shoreline. The uncertainties related to the calculations of the surface areas of change were also estimated. The equation used (E_{g2}) is similar to E_{g1} , with the difference that it omits the georeferencing error, which does not apply in the case of calculations of surface areas ($E_{g2} = \sqrt{E_p^2 + E_d^2}$). E_{g2} is between 1.59 (Pointe Mulâtre) and 2.75 m (Scotts Head). To determine the trend of the change in the surface areas while taking into account this margin of uncertainty, a buffer zone with a width equal to E_{g2} was subtracted from the polygons. Their surface area is expressed as a raw value (m^2) or with respect to the length of the segment of the coastal cell studied (m^2/m) according to $\frac{\text{polygonsurfacearea}}{\text{shorelinestudied}(l)}$, where l is the average length of the digitised shorelines for each site.

Table 3 Uncertainty indices for the position of the shoreline calculated for each site

3.5. Evaluation of the morphological impact on the coast

The impact of the hurricane on coastal features was evaluated via qualitative observations supplemented by topo-morphological surveys. These field observations were carried out in the month of March 2019, or 18 months after the passage of Hurricane Maria. This interval of 18 months was a challenge to the recognition of the morpho-sedimentary effects of the hurricane, which were sometimes tenuous or even erased. This raises questions about the preservation of deposits from extreme events over a long time for paleoenvironmental studies. However, the absence of a major hydrometeorological event in

this period favoured a preservation of the coastal features sufficient to allow the detection of the impact of the hurricane. A hydro-morphological map was produced for each site. It was based on the identification, through the features of the landscape, of the processes induced by the hurricane and their effect on the ecosystems and structures. The visible features such as the deposits, ablation marks, or movements of material, as well as the impact of the storm winds and swells on the vegetation and on structures, were inventoried and mapped. Furthermore, the limits of the marine and fluvial deposits of debris and sediments (Cariolet 2010; Morton and Sallenger 2003; Wang and Horwitz 2007) allowed the overall flood limits, i.e. of marine and river flooding, to be determined for the sites of Portsmouth Bay, Colihaut, Mahaut, Grand Bay and Pointe Mulâtre. When the visible features allowed it (7 out of 9 sites), it was possible to measure the maximum water levels reached by the wave run-up and the flooding and compare them to the data of Heidarzadeh et al. (2018). This work was supported in parallel by the accounts of inhabitants and the observation of aerial images or of very-high-resolution (LiDAR, UAV) digital elevation models (DEM).

3.6. Evaluation of the impact on coastal structures

The analysis of the impact of the hurricane on coastal structures involves two types of structures: the road network, including bridges and fords, and the buildings of the coastal villages studied. To evaluate the impact of the hurricane on the road network, a database on the operational state of the coastal sections of roads was produced. Two types of information were recorded: (i) the degree of disruption of the sections of road and (ii) the operational state of the bridges and fords. The former comes from the accessibility maps of the island produced by the NGO World Food Programme (WFP) for 6 dates in the post-storm period: 25/09/2017, 28/09/2017, 03/10/2017, 04/11/2017, 24/11/2017 and 12/01/2018. In addition to these dates, field observation of these same sections of road on 01/04/2019 allowed their state to be evaluated almost 18 months after the event. The second type of information was provided by a former road supervisor for the Ministry of Public Works. This information relates to the state of all the bridges and fords on the west coast between Capuchin and Roseau in the days after the hurricane. Like for the sections of road, the field observations on April 1 and 2, 2019 allowed the state of the same bridges and fords to be updated 18 months after the hurricane. The field observations also allowed the nature of the impact of the hurricane on the buildings on the coast to be qualified. This evaluation was supplemented by the analysis of the Building Damage Assessment (BDA) database produced by the United Nations Development Program (UNDP) in cooperation with the World Bank and the government of Dominica. The latter inventoried the level of damage to more than 29,000 buildings over the entire island between October 2017 and January 2018 through the work of teams in the field. For our study, we selected the buildings located at the study sites according to two criteria: they were located in a zone less than 1 km from the shoreline studied and inside the associated catchment areas. The lack of accuracy of the geolocation of the buildings evaluated in the BDA excluded a cartographic analysis of the damage.

4. Results

4.1. Atmospheric characteristics of the hurricane

The outputs of our 90-meter-scale gust model showed that the highest peak gusts, above 300 km/h, were located over the sea on the northwest side of the island (Fig. 5a). In general, the sea surface gusts decreased over land. The main explanation for this may be the complex topography, which induced a strong wind shear that destabilised the vortex during landfall. The land-use roughness also contributed to decelerating the surface gusts. However, peak gusts above 250 km/h were simulated along some crests. This 90-meter-scale numerical simulation showed very good agreement with the available observations described in Pasch et al. (2019). At the Canefield station, the simulated peak gust value and the observed value were 220 km/h and 215 km/h, respectively. At the Belles station, the simulated peak gust value and the observed value were respectively 141 km/h and 135 km/h. The rainfall outputs have a horizontal resolution of 280 m (Fig. 5b,c). The northern part of the island's mountain crest was more affected by the extreme precipitation occurring in the most intense quadrant of the eyewall. The maximum simulated 24-h rainfall reached 610 mm near the summit of Morne Diablotins. A comparison to the recorded 24-h accumulated rainfall from four stations (Canefield, Salisbury, Pond Casse and Belles (Dominica Meteorological Service 2017)) revealed slight model underestimations with a mean bias error of -41 mm. To better understand the devastating floods, the simulated maximum rainfall rates per hour were also examined (Fig. 5c). The maximum simulated rainfall rates, above 150 mm/h, occurred in the north of the mountainous part of the island. In the southern half of the island, the peak rainfall values (around 80-110 mm/h) observed during Tropical Storm Erika (2015) were reproduced for Hurricane Maria (Nugent and Rios-Berrios 2018). This would explain some similarities between the two storms in terms of river flood damage in this area, which is characterized by very steep terrain. At Copthall station (located 120 m above sea level), the Dominica Meteorological Service (2017) reported an extreme rainfall rate of 289 mm/h, associated with a 5-min accumulated rainfall of 83 mm. These extreme rainfall values seem unrealistic since they are much greater than any observed on the island for Hurricane Maria or Tropical Storm Erika (Dominica Meteorological Service 2017; Nugent and Rios-Berrios 2018). The Copthall rain gauge is located on a bridge that was flooded by the river during Maria. These unrealistic rainfall values could have been caused by the flooding of the rain gauge. The observational rainfall data recorded by the Copthall station has not been taken into account in the present study. Based on the observational data from the previous four stations, the model tends to slightly overestimate the observed rainfall rates, with a positive mean error bias of 16 mm/h. This trend towards slight overestimation of the maximum rainfall rate by the model needs to be balanced with the potential rain gauge underestimation generated by the hurricane-force winds.

Fig. 5 Model results: maximum gust values in km/h at 90-m scale (a), 24-h accumulated rainfall in mm at 280-m scale (b), and maximum rainfall rates in mm/h at 280-m scale with the main river network (c)

4.2. Hydrodynamic characteristics of the hurricane

The maximum significant wave height (H_s) was found to be greatest north of the track, where it reached 7-10 m offshore (Fig. 6). Most of the eastern coast was directly exposed to high-energy waves that propagated towards the shore at the peak energy. A notable exception is the north-facing coast close to the village of Calibishie, where the most energetic waves propagated along the shore. The leeward coast is more sheltered, with H_s not exceeding 5 m offshore. The mean wave direction in deep waters at the peak energy displayed a rotating pattern as a function of latitude, with offshore waves propagating to the SW in the north and to the SE in the south. This led to larger waves at the shoreline in the southern regions, which is consistent with the observations of

Heidarzadeh et al. (2018). The maximum was reached in Scotts Head, with an Hs of about 5 m close to the shore. According to our models, the surge did not exceed several dozen centimetres, except in small bays close to the storm track, where it may have locally exceeded 1 m. The maximum water level predicted at the tide gauge located at Marigot is about 70-80 cm, in good agreement with the observations (Heidarzadeh et al. 2018).

Fig. 6 Maximum significant wave height and mean wave direction at the peak energy, computed by the numerical model (a) and maximum water level (relative to mean sea level) (b) The dashed white line represents the track of the hurricane

4.3. Impact of the hurricane on the position of the shoreline

The passage of Hurricane Maria led to an advance of the shoreline for most of the sites studied. For 7 of the 9 study sites (Colihaut, Fond Saint Jean, Grand Bay, Mahaut, Petite Savanne, Pointe Mulâtre, Scotts Head), the mean net shoreline movement (NSM) varied from 2.43 to 74.58 m, and an advance of 1.72 to 56.35 m²/m was observed in terms of surface area.

Fig. 7 Change in the position of the shoreline caused by the passage of Hurricane Maria in Grand Bay (a), Petite Savanne (b), Mahaut (c) and Portsmouth Bay (d)

4 of these sites (Colihaut, Fond Saint Jean, Grand Bay, Petite Savanne) exhibited a remarkable extension of the shoreline, with more than 80% of the transects having a positive NSM value and a gain in surface area between 9.45 (Colihaut) and 56.35 m²/m (Petite Savanne - Fig. 7b). The maximum NSM values recorded for these sites varied between 14.84 and 74.58 m. At Mahaut (Fig. 7c), Pointe Mulâtre and Scotts Head, the trend was more moderate in terms of progradation, with mean NSM values of 2.43, 2.69 and 3.76 m, respectively, and gains in surface area of 1.77, 1.72 and 2.23 m²/m (Table 4). The transects considered to be stable were mostly at Mahaut and Scotts Head (61.21 and 65.98%). However, significant variations appeared locally where the minimum NSM values reached about a dozen metres for Mahaut (-12.81 m) and Pointe Mulâtre (-12.47 m). Number One Beach and Portsmouth Bay (Fig. 7d) stood out, with a marked erosive tendency. 100% (Number One Beach) and 68.75% (Portsmouth Bay) of the transects presented negative NSM values, with an average retreat of the shoreline of 16.34 and -8.34 m, respectively. The losses in terms of surface area correspond to these values (Number One Beach, -10.76; Portsmouth Bay, -6.28 m²/m). For these two sites, the minimum NSM values were -22.18 and 42.74 m.

Table 4 Movement of the shoreline caused by the passage of the hurricane at the study sites

4.4. Adjustments of the position of the shoreline after Maria

In the post-storm period (1 to 3 years after the passage of the hurricane), the changes in the shoreline showed contrasting tendencies. Contrary to the previous period, marked by the passage of the hurricane, the changes were characterised more by a retreat or stability of the shoreline.

Fig. 8 Change in the position of the shoreline in the post-storm period in Grand Bay (a), Petite Savanne (b), Mahaut (c) and Portsmouth Bay (d)

A contraction of the shoreline was observed for 4 of the 9 sites (Fond Saint Jean, Grand Bay, Petite Savanne and Pointe Mulâtre), with the average of the NSM values varying between -3 (Fond Saint Jean) and -9.38 (Grand Bay, Fig. 8a). For these sites, the minimum NSM values varied between -13.36 (Petite Savanne) and -28.78 m (Pointe Mulâtre). Although a slight retreat was recorded at Scotts Head (-1.54 m or -0.64 m²/m), the site exhibited a certain stability: 80.21% of its transects were considered to be stable (Table 5). At the other sites (Colihaut, Mahaut, Number One Beach and Portsmouth Bay), the values recorded were especially or exclusively positive. The average NSM values varied between 3.88 (Mahaut, Fig. 8c) and 21.02 (Number One Beach), with maximum NSM values between 11.35 (Mahaut) and 41.51 (Portsmouth Bay, Fig. 8d). The beaches gained between 1.68 (Mahaut) and 14.03 m²/m (Number One Beach). After a rapid transformation of the coast, it thus begins to rebalance itself through a progressive, slower phase of returning to a previous state.

Table 5 Movement of the shoreline caused by the passage of the hurricane at the study sites

4.5. Morpho-sedimentary impact of the hurricane

4.5.1. Fluvial effects

As indicated by the analyses of the change in the shoreline, Hurricane Maria had a varied impact on coastal areas. Some experienced erosion (Number One Beach, Portsmouth Bay), while for others, the passage of the hurricane generated a more or less significant advance of the shoreline. The precipitation generated by the hurricane triggered both torrential flooding and numerous ground movements (favoured by the water saturation of the soil and the slope of the catchment areas). Thus, a large quantity of materials coming from the erosion of the slopes and the banks was transported and deposited by the streams near the river mouths, resulting in a growth of the coastal cells. The coastal changes were most spectacular at Fond Saint Jean, Grand Bay, Petite Savanne, and in a more localised manner, Pointe Mulâtre. These sites, located in the southeast part of the island, are among the coastal areas with the steepest slopes. The average slope of the catchment areas associated with these sites is 25.11%, versus 21.43% for the rest of the sites. The results of numerical atmospheric models indicate intense rainfall at these locations (between 85 mm/h and 100 mm/h maximum hourly rainfall). Significant eroded surfaces visible on the slopes (Fig. 9a) and ablation marks on the banks (Fig. 9b) bear witness to these processes of erosion.

Fig. 9 Evidence of erosion and of transport of sedimentary materials towards the river mouths. Steep slopes and landslides above Petite Savanne (a). Ablation marks on the banks of the White River at Pointe Mulâtre (b). Voluminous heterometric deposits on the beach at Petite Savanne (c). Megablock transported by the flood and deposited at the mouth of the White River at Pointe Mulâtre (d). Battut, 2019

The resulting deposits are especially visible around the river mouths, where they formed flood deltas (Fig. 10b,c). At sites with accretion (Colihaut, Fond Saint Jean, Grand Bay, Mahaut, Petite Savanne and Pointe Mulâtre), the mouth areas advanced at most 49 metres. The deposits observed at these locations were mainly composed of heterometric pebbles and megablocks with a diameter sometimes exceeding 2 metres (Fig. 9c,d). Large plant debris (trees, trunks) was

also deposited. The coarse deposits and the diffluences (Fig. 10b,c) observed in the coastal plain attest to the energy of the streams during the passage of the hurricane. At Grand Bay, Petite Savanne and Pointe Mulâtre, the dynamics of the mouths exhibited a similar organisational model: the central part of the delta, surrounded by active channels during the event, contained most of the coarsest deposits. It consisted of an axial succession of deposit lobes that extended to the shore. Deposits of fine materials (fine to coarse sand) were found on either side, indicating a loss of competency related to the abandonment of a secondary channel (Fig. 10b,c). The deposit phenomena described were also visible at Colihaut, where a large part of the built-up area, low lying or in the flood plain, was flooded during the passage of the hurricane, as shown by the reconstruction of the overall flood-extent map (coastal and river flooding) (Fig. 10a). The flood deposits reached a height of up to 2 metres on the banks of the Colihaut River (Fig. 10a). Like for Petite Savanne, Pointe Mulâtre and Grand Bay, the particle size of the deposits was heterogeneous, with a majority of pebbles and blocks between 10 cm and 1.50 m in diameter.

Fig. 10 Hydrosedimentary morphological impact of Hurricane Maria. Overall flood extent (river and coastal flooding) in the village of Colihaut (a). Diachronic map of the mouth of the Geneva River in Grand Bay (b). Diachronic map of the mouth of the White River at Pointe Mulâtre (c).

The heterogeneity of the materials and the river dynamics during this extreme event confirm the importance of fluvial processes in the progradation of the coast, but the latter very probably cover up the role of marine processes, in particular at the river mouths.

4.5.2. Marine effects

Fig. 11 Morpho-sedimentary impact of marine origin at Number One Beach : exposed root system of coconut trees (a), washover deposits with mats of *Ipomoea pes-caprae* (b), coral rubble deposited by waves (c), washed action on a seafront cliff (d), washover deposits and fallen coconut trees (e).

The swell and the storm surge caused by the passage of the hurricane also participated in the morphological changes on the coast. The temporary rise in the sea level and the breaking waves flooded the low-lying areas of the waterfront. The maximum wave run-up was estimated at Colihaut (2.5 m), Grand Bay (2.4 m), Mahaut (3 m), Number One Beach (2.5 m), Pointe Mulâtre (2.8 m), Portsmouth Bay (1.5 m) and Scotts Head (4 m). These values coincide with the numerical results, which assign the greatest wave heights (approximately 5 m) around the Cachacrou Peninsula (Scotts Head). While all of the sites were affected by the storm swell, the models indicate that the storm surge affected above all the coastal areas of the centre of the island (Fig. 5). The wave run-up recorded at Colihaut may thus have been amplified by a storm surge of approximately 70 cm. The biogeomorphological evidence of marine effects is most present at Number One Beach, Portsmouth Bay and Scotts Head. When the topography allowed it, the flooding and the breaking storm waves transferred sedimentary material from the foreshore to the backshore, dunes, and even beyond. These transfers are visible at Number One Beach in the washover that extends behind the beach, up to 30 m from the shoreline (Fig. 11e). Similar features are visible in the least artificialised zones of Portsmouth Bay. Mats of *Ipomoea pes-caprae* are abundant in this washover (Fig. 11b). This creeping vine likes to colonise fresh deposits and dynamic substrates and may constitute a biological indicator of recent sediment accumulation in the supratidal zone (Devall 1992; Heatwole et al. 1981). Also abundant at the three sites, coral blocks and rubble deposited on the backshore attest to these transfers of sediment and the energy of the swell during the event. Coral blocks with a maximum diameter of approximately 20 cm, 30 cm and 70 cm were observed at Portsmouth Bay, Number One Beach and Scotts Head, respectively. Such deposits were also observed in Grand Bay, Pointe Mulâtre, Mahaut and Colihaut, but only on the edges of the river mouths. The impact of the waves and the erosion of the beaches on the coastal flora is essentially visible in the introduced vegetation (*Cocos nucifera*), a part of the root system of which was exposed (Fig. 11a). In the sectors marked by the presence of natural (scarp, cliff, stabilised dune) (Fig. 11d) or anthropic (buildings, protective structures) obstacles favouring the reflection of the incident swell above the beach, a horizontal contraction and a vertical erosion of the beach (Fig. 12a) were observed. At Number One Beach (Fig. 11) and Portsmouth Bay, as well as Pointe Mulâtre (Fig. 10c) and Grand Bay, the impact of the swell on the dunes stabilised by vegetation (mainly *Sporobolus virginicus* and *Vigna marina*) led to the formation of scarps and dune cliffs (Fig. 12c). At Scotts Head, the flood debris (sand and pebbles) perched at a height of up to four metres in the crevices of the walls and protective structures bear witness to the effects of the vertical swash related to the breaking of the waves on a subvertical obstacle (Fig. 12b). In addition to the sediment and coral deposits, large quantities of plant debris accumulated on the beaches (Fig. 10b,c). This debris is the result of vegetation being uprooted by the wind, but especially by ground movements and torrential flooding, which transported this debris to the river mouths, where the storm swell rearranged it and deposited it on the backshore. Thus, ligneous deposits were significantly more present at the sites where the river dynamics were the most visible (Colihaut, Grand Bay, Pointe Mulâtre, Petite Savanne).

Fig. 12 Impact of the storm swell on the various vertical surfaces of the seafront. Protective wall at Portsmouth Bay (Coconut Beach) (a), Retaining wall at Scotts Head (b), dune cliff at Pointe Mulâtre (c). Battut, 2019

4.6. Impact of Hurricane Maria on coastal structures

4.6.1. Damage to buildings

According to the BDA, almost 73% of the buildings on the island experienced roof damage of more than 25%. At the study sites, 16.91% of the buildings experienced no damage or less than 25% damage to the roof (minimal damage), 25.00% had just roof damage of more than 25% (minor damage), 20.31% had serious damage to the roof and walls (major damage), and 15.30% of buildings were completely destroyed (Table 6). The buildings experienced the most damage in Fond Saint Jean and Grand Bay, with a rate of destruction of 29.41% and 31.28%, respectively. The total of buildings with major damage or destroyed is close to 60% of all of the buildings selected in the coastal zone in Colihaut, Fond Saint Jean, Grand Bay and Scotts Head. Mahaut and Portsmouth Bay, although more densely urbanised, were less severely affected by the passage of the storm, with a rate of destruction of 10.29% and 20.25% and a rate of major building damage of 28.24% and 22.28%, respectively.

Table 6 Level of damage to buildings at study sites according to the BDA. There are no buildings within 1 km of the shoreline at Number one Beach and Petite Savanne

The nature of the damage to the buildings in the coastal zone depended on their exposure to storm hazards. The torrential flooding and ground movements triggered by Hurricane Maria were responsible for significant damage in the coastal areas, mainly in Colihaut, Mahaut, Grand Bay and Fond Saint Jean, where some of the buildings are located in alluvial plains or on the banks and in the flood plains of streams that behave like torrents. In Colihaut, for example, flows of debris in the bed of the Colihaut River passed through the first floor of about twenty homes located on its banks (Fig. 13a,b). In Grand Bay and Fond Saint Jean, the floodwaters scoured the banks, destabilising buildings and structures and sweeping away some homes (Fig. 13c). In both cases, the damage was accentuated by the projection of materials onto buildings and infrastructure and by the creation of logjams in culverts too small for such an event. For the buildings located in low-lying areas and in the immediate vicinity of the shore, as is the case at Portsmouth Bay, Colihaut, Mahaut and Scotts Head, the waves of the storm swell also participated in the damage to buildings. The mechanical action of the waves and the marine flooding led to a scouring of the soil at the base of the retaining walls and of the buildings, which, conjointly with the impacts and pressure caused by the breaking waves and the turbulence of the waters, led to the tilting and/or collapse of these structures. The orientation of the rebar of the damaged concrete structures attests to the tilting of the vertical structures under the effect of the waves (Fig. 13e). These phenomena are responsible for the destruction of several homes and businesses on the waterfront in Scotts Head (Fig. 13d) and Portsmouth (Lagoon neighbourhood). They also led to the death of one person in their home on the waterfront in Scotts Head.

Fig. 13 Various types of damage to buildings associated with the passage of Hurricane Maria. Fluvial sediment deposits in Colihaut (a). Ground floor of a home submerged by the flood deposits in Colihaut (b). Home partly swept away by a flooded stream in Berekua, Grand Bay (c). Waterfront home partly swept away by the storm swell in Scotts Head (d). Rebar from the destroyed walls of a waterfront building bent by the storm swell in Scotts Head (e). Battut, 2019

Port structures such as jetties were greatly damaged by the swell. In Portsmouth Bay, 4 minor jetties were totally destroyed and one of the three main jetties (the Cabrits Cruise ship berth) was significantly damaged. In Mahaut, the two main jetties were severely affected by the swell. The fishing infrastructure was hit particularly hard by the passage of the hurricane: approximately 15% of the fishing boats were damaged or destroyed (Government of Dominica 2017). This was the case in Colihaut, Mahaut and Scotts Head, where most of the boats and waterfront facilities (huts and small mooring areas) were destroyed by the storm swell. Finally, the hurricane winds affected most of the buildings at all the study sites, sometimes adding to the river and marine damage. The wind damage is especially visible in the damage to roofs, which were more than 25% damaged for almost 80% of the buildings.

4.6.2. Damage and repairs to the road network

The road network is of crucial strategical interest in Dominica. It is responsible for most of the transport of goods and people and plays an important role in the development of the tourism sector. The polarisation of the national territory by the capital, Roseau, which is home to most services, makes necessary a certain geographic continuity that allows the less dynamic peripheral areas, in particular in the eastern half of the island, to be connected. The passage of Hurricane Maria caused the destruction or obstruction of many sections of road, hindering access to isolated villages and forming a lasting obstacle to the recovery of the territory in the post-crisis period. On September 25, 2017, or a week after the passage of the hurricane, a large part of the main coastal road along the western façade of the island was either totally blocked (from Roseau to Soufrière) or strewn with debris and rocks and only accessible to off-road vehicles (from Roseau to Portsmouth) (Fig. 15). In the months after the passage of the hurricane, the reconstruction of the road network was highly unequal among to the geographic sectors. While the section from Portsmouth to Capuchin was very quickly restored after the hurricane, certain sections of road in the southwest of the island were only operational almost 2 months after the event. More precisely, the road sections from Roseau to Laudat, from Castle Comfort to Giraudel, and from Pointe Michel to Scotts Head (Fig. 15c) remained cut-off for the longest. In these sectors, the topography favoured the triggering of numerous ground movements, which required heavy repair works and thus contributed to slowing down the road repair. Indeed, the time needed to repair a road seems to be correlated to the longitudinal slope of the road section and to the surrounding relief (Table 7).

Table 7 Topographic characteristics of west-coast roads and their repair date according to WFP reports

The section of road from Soufrière to Scotts Head, which is flat, forms an exception to this trend. In this sector, the storm swell was responsible for the scouring of the fill, which led to the collapse of the pavement (Fig. 14b), and deposited plant debris and blocks from the foreshore (Fig. 14a).

Fig. 14 Wave impact on Scotts Head seafront. Coarse deposits of marine origin on the pavement in Scotts Head (a). Coastal Road heavily damaged by the storm swell between Soufrière and Scotts Head (b). Photographs by Gemma Handy (BBC News 2017)

But the most significant damage occurred at the intersections of streams and roads, where the river discharge and the material carried by the floods eroded, swept away, or blocked the bridges and fords. Between Capuchin and Roseau, on the west coast, we identified a total of 35 bridges and 109 fords. Among them, 21 bridges (60%) and 94 fords (86.24%) were slightly damaged, submerged, or blocked but remained operational after the passage of the hurricane, while 14 bridges (40%) and 15 fords (13.76%) were destroyed or very severely damaged. Most of the damage took place in the region of Roseau, where the flooding of the Roseau River destroyed 4 bridges and 3 fords, and in the centre west of the island, between Tarou and Dublanc. Under normal conditions, the average repair time is 1 month for a ford and 3 to 4 months for the average bridge. On April 1, 2019, or 18 months after the passage of the hurricane, 96.32% of bridges and fords were operational, while 3.68%, or 3 bridges and 2 fords, were still being rebuilt or finished. Priority was given to the reconstruction of the damaged structures in the main urban areas (Roseau, Portsmouth). The structures still being repaired in April 2019 were fords and minor bridges. They were all located between Dublanc and Macoucheri, in the central part of the west coast (Fig. 15a,b). In these locations, the bypass of the bridges and fords under construction by vehicles was ensured by the installation of temporary metal structures.

Fig. 15 Recovery of road network and water-crossing structures in the aftermath of Hurricane Maria on the west coast of Dominica. Capuchin to Colihaut (a). Coulibistrie to Massacre (b). Canefield to Scotts Head (c). Road states refer to these 7 dates, in chronological order from the centre to the outside of the line: 25/09/2017, 28/09/2017, 03/10/2017, 04/11/2017, 24/11/2017, 12/01/2018 and 01/04/2019. Landslides that directly affected roads were detected using very-high-resolution orthophotography from October 2018

5. Discussion

5.1. Variability and specificities of the effects of the storm on the coastal landscapes

The analysis of the impact of Hurricane Maria on the coastal areas of Dominica has highlighted the variability of the morpho-sedimentary responses. These responses, studied by monitoring the change in the position of the shoreline, were confirmed in the field by topo-morphological observations and surveys. The results bring to light three types of responses:

- The first type characterises the sites (Colihaut, Fond Saint Jean, Petite Savanne, Grand Bay) where the fluvial processes were dominant in the modification of the landscape. This translated into massive sedimentary injections in the coastal cells, resulting in a significant expansion of the beaches, to a lesser extent also related to the action of the sea.
- The second type of response to the hurricane qualifies the sites (Pointe Mulâtre and Mahaut) where the dominance of marine or fluvial phenomena in the modification of coastal features was not established as clearly. The changes at these sites were less radical. The surface area of the delta progradation observed at river mouths was more limited because of less voluminous fluvial sediment deposits. In the rest of the cell, the impact of the action of the sea was more present than for the first type of response.
- The third type includes the sites (Portsmouth Bay, Number One Beach, Scotts Head) characterised by the prevalence of a marine influence (storm swell and marine flooding). For these sites, there was a transfer of sediment among the various parts of the coastal system (foreshore, beach, backshore), with a consequential erosion or growth of the beaches.

The response of the coast to the hurricane was thus influenced by two main types of forcing: (i) an essentially fluvial constructive tendency, related to processes of sedimentation in the catchment areas, and (ii) a mostly erosive tendency related to the action of the storm swell. The prevalence of one or the other of these forcings is closely related to the topographical configuration of the catchment areas and the slope of the streams. The greater the slope of the streams, the more significant the sedimentary discharge towards the coastal cells, resulting in the growth of the beaches and an advance of the shoreline (Fig. 16).

Fig. 16 Relationship between the mean slope of the main rivers and catchment areas associated with each study site and the mean net shoreline movement (NSM)

At Number One Beach and Portsmouth Bay, the smoother topography of the catchment areas and the lower slope of the main streams (Hampstead River and Indian River), the mouths of which resemble estuaries, favoured the prevalence of marine effects. In Scotts Head, the absence of a perennial stream limited the sediment discharge from the slopes. The fine materials (fine to coarse sand) forming the beaches of Number One Beach and Portsmouth Bay, unlike all the other beaches, which are essentially composed of pebbles, also may have promoted their sensitivity to marine and wind erosion and may explain the overall retreat of the shoreline.

Overall, the response of the Dominican coast to Hurricane Maria signals the importance of fluvial dynamics in the modification of the coastal landscapes. This situation differs from other tropical island coasts, such as in Saint-Barthélemy and Saint-Martin, where there are no major streams and the growth of the coast was substantially related to the action of the swell during the passage of Hurricane Irma in September 2017 (Pillet et al. 2019; Rey et al. 2019). This situation is specific to humid, well-drained mountainous coasts, which are more favourable to phenomena of intense sedimentation (Gupta 2000; Korup 2012). The major role of extreme meteorological events such as tropical storms in the triggering of erosive processes (ground movements and/or major river floods) in the catchment areas of this type of coast has been widely demonstrated (Allemand et al. 2014; Bravard et al. 2001; Galewsky et al. 2006; Gupta 2000; Page et al. 1994, 1999; Terry et al. 2002, 2006). Besides the slope of the terrain and the nature of the substrates, the intensity of these phenomena is especially influenced by the quantity of precipitation produced during storms and hurricanes. Therefore, even a low-intensity event in terms of wind speed can cause damage of large magnitude. This is the case for Tropical Storm Erika, which passed over Dominica in August 2015 and was one of the most noteworthy natural disasters in terms of material damage and loss of human life in recent times (Pasch et Penny 2016). Contrary to the winds and intense precipitation of Hurricane Maria, the values for the storm surge, wave height, and wave run-up were of moderate intensity in Dominica. In accordance with the results of our numerical model, our observations and those of Heidarzadeh et al. (2018), the maximum swash height recorded was on average 2.5 m and did not exceed 4 m. These values are relatively low compared to those recorded during the passage of Hurricane Irma over Saint-Martin and Saint-Barthélemy, where the maximum run-up heights reached 6 m on the sandy coasts and up to 10 m on the rocky coasts (Cangialosi et al. 2018; Rey et al. 2019).

5.2. Adjustment of coastal cells after the hurricane

After the rapid and sometimes radical morphological changes induced by the passage of the hurricane, the coastal morpho-systems implemented progressive biophysical adjustments over the medium term ($t+1$ to 3 years). Although the features (coarse biogenic and sedimentary deposits, flood deltas) resulting from the event are still visible in the landscape, coastal currents, floods, and minor storms have dulled and attenuated them little by little. The sediments accumulated in the prograding cells were very probably either redistributed from the mouths to the other cells or transferred towards the shoreface or offshore, with a consequential retreat of the shoreline (Table 8). These processes are masked in Colihaut and Mahaut, where earthworks on the beaches artificially advanced the shoreline around the river mouths. Inversely, in areas where the storm swell caused the erosion of the beaches (Number One Beach, Portsmouth Bay), a trend of growth was observed in the post-storm period (Table 8).

Table 8 Comparison of beach responses to and after the hurricane in terms of calculated NSM

The rhythm and nature of the recovery of coastal systems depend on the state of degradation of the coastal ecosystems before and after the storm (Woodroffe 2007) and on the frequency of storms (Houser and Hamilton 2009). In the case of Portsmouth Bay, the erosive tendency related to the passage of

Hurricane Maria had already been expressed during the hurricanes Hugo (1989), David (1979) and Lenny (1999). For example, Cambers and Arlington (1994) measured the lost surface area of beach at 33% (Lagoon) and 55% (Coconut Beach) after the passage of Hugo. One example of degradation of coastal ecosystems is the poor state of the coral reefs, the ability of which to dissipate the energy of the swell (Young 1989) and feed the beaches (Etienne and Terry 2012) has been established. Steiner (2015) reported a severe deterioration of the reefs around the entire island; they have been exploited since colonial times, when they were used as mortar for the construction of foundations and fortifications (Honychurch 1995). Today, certain fishing techniques and the pollution of the river water continue to deteriorate the coral reefs (Steiner 2015), thus limiting their protective effect for the coast. More significantly, the recovery of the coastal systems is influenced by the level of artificialisation of the coastline. In Portsmouth Bay, Mahaut and Scotts Head, the urbanisation and the setting of the waterfront have had the effect of amplifying the energy of the swell and aggravating its impact on buildings, roads and protective works. Since the transfers of sediment between the various zones of the beach and the backshore are hindered or even made impossible, the backshore can no longer play its role of restoring the stock of sediment in the recovery phase. Consequently, the reestablishment of the eroded beaches in the most urbanised sectors is much slower than on natural beaches such as Number One Beach, where the deposits of sand stored on the backshore were able to be restored to the foreshore, and where the vegetation has already begun to recolonise the waterfront. Only long-term monitoring will allow the trends to be analysed and Hurricane Maria to be defined as either an epiphenomenon, with a return to a pre-hurricane morphological configuration, or a paroxysmal event responsible for a permanent change in the coastal dynamics. This morphological trajectory will depend on factors both natural (intensity and frequency of the next storm events, available sediment sources, coastal transfers, morphology of the coast and of the catchment areas) and anthropic (extraction of the sand, artificialisation of the coast, pollution, and deforestation) (Moulet and Saffache 2006; Woodruff et al. 2013).

5.3. Exposure and vulnerability of coastal settlements

The mountainous nature of Dominica limits the flat surfaces that can be easily built up to the coastal plains, and often, in particular on the west coast, to alluvial plains and fans (Fig. 1). Consequently, the main urban zones are in these low-lying areas highly exposed to hydrometeorological risks. The concentration of the population of Dominica on the coast is also the result of the organisation of the territory during the colonial period, which was oriented towards exportation (Clarke 1974) and characterised by sociospatial segregation (Baker 1994; Barclay et al. 2019; Honychurch 1995). Over the last few decades, the emergence of the tourism sector as a substitute for the agricultural sector, in particular given the decline of banana cultivation in the 1990s (Weis 2018), contributed to reinforcing the urban pressure on the coast with a migration of rural populations to the urban centres (Weaver 1991). Between 1960 and 2018, the urban population grew from just under 22,000 to more than 50,000 people (United Nations 2018a), while the rural population decreased from 60,000 to 29,000 (United Nations 2018b). Consequently, despite the low population density and low amount of anthropisation of the environment with respect to the other islands of the Antilles, and more broadly the islands of the Caribbean, the population and infrastructure of Dominica remain highly exposed to hydrometeorological risks.

The analysis of the impact of Hurricane Maria on coastal structures has revealed the vulnerability of the buildings and infrastructure (roads, bridges, fords, coastal protective structures) of Dominica to a very-high-energy event. The rates of destruction and critical damage to buildings were very high in the study sites (20.34% of buildings destroyed and 25.97% of buildings with major damage) and for the island in general (18.44% of buildings destroyed and 25.53% of buildings with major damage). The evaluation of the damage to buildings indicates that the use of unsuitable materials and construction techniques increased the damage done. The lack of financial capacity is in all likelihood the main cause because it influences the choice of materials, the surface area, and the techniques of construction of buildings, which are selected according to their cost. For example, roofs made from galvanized metal, which are the most common and the least expensive, suffered more damage from the hurricane than the roofs made from reinforced concrete or cement (Fig. 17a). This is also visible in the size of the buildings. The smallest buildings (less than 46 m²), less costly and often self-built, are overrepresented (66.59%) among the destroyed buildings (Fig. 17b).

Fig. 17 Relationship between the damage level of assessed buildings and their roof materials (a) and size (b). Source: BDA

In addition to aggravating the potential damage, the architectural unsuitability of the buildings may place the lives of their occupants in danger. The analysis of the causes and circumstances of the deaths during extreme hydrometeorological events (storms, hurricanes, and floods) in Guadeloupe between 1950 and 2018 brought to light the link between building unsuitability and mortality (Leone et al. 2019). Before the 1970s, a large portion of the deaths resulted from damage to buildings, which, instead of protecting their occupants, could be responsible for their death. The efforts undertaken by the local government since then to make buildings hurricane-proof, along with other reforms, have significantly reduced the loss of human life.

Like for the buildings, Hurricane Maria brought to light the vulnerability of Dominica's road network to hydrometeorological events. The dimensioning and the design of the structures (pavements, bridges, fords, coastal protective works) turned out to be unsuitable. This situation is not new in Dominica; because of its relief and precipitation regime, the development and maintenance of the road network has been a major problem for the government ever since the arrival of European colonists (Honychurch 1995). The numerous attempts to connect the various inhabited areas, and then the locations of agricultural production, often failed. In most cases, the cost of construction ended up being greater than the allocated funds, in particular because of rain and ground movements (Honychurch 1995; Baker 1994). Starting in the 1950s, financing for the construction of roads increased and the main inhabited areas were finally connected. But the lack of investment due to the desire of the colonial authorities to maintain the construction costs as low as possible, the irregular maintenance of structures, and a period of calm in terms of hydrometeorological events (Honychurch 1995; Benson et al. 2001) resulted in the risks, in particular hydrometeorological, not being properly taken into account in the design of the infrastructure and a rapid degradation of the structures. These problems persisted after the country's declaration of independence; its weak financial capabilities extended its dependence on outside aid and forced it into debt to finance the road infrastructure. Persistent technical failures were brought to light by the substantial damage to the road network caused by the hurricanes David (1979), Hugo (1989), and Lenny (1999) and Tropical Storm Erika (2015). The passage of Hurricane Maria (September 2017), only two years after Erika (August 2015), struck a territory already fragilised and still in the recovery phase. For example, three bridges on the west coast (Macoucherie, Pointe Ronde and Batalie) were still under repair when Maria hit and were not reopened until July 2020, or almost 5 years after their destruction (Dominica Vibes 2020a).

Likewise, the section of road connecting Petite Savanne to Delices on the east coast, cut off by Erika and further degraded by Maria, was only reopened in September 2020 (Dominica Vibes 2020b). The role of road infrastructure in the post-crisis recovery phase is crucial in the short and medium term. Its operational status determines the accessibility of peripheral areas to rescuers and the provision of vital resources to these areas. In terms of daily life, geographically isolated sectors often lack sufficient access to resources and services, which can be a vulnerability factor even further exacerbated during natural disasters (Zakour and Harrell 2004). This is the case of certain highly-impooverished isolated communities (Ballini et al. 2009) in the northern and eastern parts of the island, which include in particular the Kalinago Territory. The passage of Hurricane Maria temporarily cut off access to certain villages such as Scotts Head, and one family ended up trapped in their property in Eggleston for almost a month after the event (The Sun Dominica 2018). Likewise, in August 2015, all road access to the village of Delices was cut off for almost two months after Tropical Storm Erika, hindering the recovery of residents, who were forced to pick up essential supplies by foot in the neighbouring villages (Dominica News Online 2015).

5.4 Lessons to be learned for the management of hydrometeorological risks in Dominica

The observations and surveys brought to light the importance of sedimentation phenomena in the catchment areas and their impact on low-lying coasts during storm events. This situation had already been observed before in Dominica and other mountainous islands (Allemand et al. 2014; Galewsky et al. 2006; Page et al. 1994; Terry et al. 2002), but Hurricane Maria reinforced the importance of considering all storm risks (wind, river and marine flooding, ground movements, and swell) and their interactions for the reduction of disasters. At-risk areas should also be mapped as precisely as possible in order to update them with regard to the new hazard reference formed by Hurricane Maria and thus be able to apply mitigation measures such as the relocation of vulnerable objects and populations, when possible, or the adaptation of buildings and structures. Such efforts have already begun, with the construction of several hurricane-proof residential neighbourhoods located in relatively safer areas and intended to house the most destitute victims of Maria and Erika, or the training of construction-industry entrepreneurs and workers in the techniques of hurricane-proof construction. Additional efforts must be undertaken in terms of relocation and adaptation of vulnerable objects and populations in the coastal flood plains, which see the most significant damage. In parallel, the reconstruction and the adaptation of transport infrastructure according to the principles of *Build Back Better* form a necessary step for the connection of peripheral areas to the rest of the island, which would have a positive impact both on daily life and in the case of a natural disaster. With regard to the spaces in the immediate vicinity of the coast, the strategic retreat of objects where possible, while re-naturalising the seafront and re-establishing its role as a buffer zone, would improve the capacity of the beaches to absorb the energy of storm waves while considerably limiting damage of marine origin in the coastal villages (Duvat et al. 2019; Rey et al. 2019; Sigren et al. 2018). The restoration of the dunes and the return of vegetation to the beaches would reduce their vulnerability to marine erosion (Feagin et al. 2019; Smee 2019) and promote their recovery after a high-intensity event. With the reduction of coastal pollution and the preservation of the coral reefs, this would contribute to maintaining the landscape and ecosystem value of Dominica on which its niche tourism sector is based (Dehoorne et al. 2009; Weaver 1991; Weis 2018). Maintaining the touristic appeal is even more important given that all these measures depend on massive investment in infrastructure and buildings over the entire island. Besides the importance of the tourism sector and the role of international aid, the Dominican government has found an additional source of revenue in activities of fiscal optimisation, including a program of Citizenship by Investment (CBI) created in 1993; this additional revenue has been successfully invested in reconstruction, health, and education. Beyond the structural measures, the interest of preparation, warning and evacuation should not be forgotten. They reduce human and material losses with little cost involved. In this respect, storm shelters, if they are properly built and well located, can effectively protect people that are not capable of making their home hurricane-proof or live in highly exposed areas. Finally, accounts of the disaster have often highlighted the importance and the value of the principle of mutual aid, or *koudmen*, throughout all the stages of the storm crisis (Philogene Heron 2018). This tool should thus be taken into account and put to good use in the management of risks in Dominica, for example by reinforcing the actions of risk mitigation on the community scale.

6. Conclusion

The goal of this article was to evaluate the responses and adjustments of the coastal areas of Dominica after an extreme event: Hurricane Maria. The use of various data (modelling, aerial and satellite images, reports, databases, eyewitness accounts), as well as field observations and surveys at 9 coastal study sites, has provided a broad overview of the impact of the hurricane. The analysis of the change in the position of the shoreline brought to light variable responses that were corroborated by geomorphological observation on the ground. The morphosedimentary signature of the hurricane is characterised in 4 of the 9 sites by spectacular sedimentation phenomena in the catchment areas, which resulted in a significant growth of the beaches, with an average advance of the coastline ranging from 14.85 m to 74.58 m. The flooded streams greatly damaged the coastal structures located in their floodplains and were responsible for a major, long-term disruption of the road network, destroying almost 30 bridges and fords on the west coast. 3 other sites were substantially affected by the storm swell, which mainly led to the erosion of beaches and the destruction of structures (buildings, roads and protective works) in the immediate vicinity of the shore. Overall, the effects of the hurricane on the coastal landscapes were marked by the prevalence of hydrosedimentary phenomena. According to our models, which were corroborated by our observations, the storm swell and surge were of moderate intensity overall, contrary to the precipitation, which was abundant over the entire island. This situation is closely linked to the mountainous nature of the island, and we have demonstrated that the slope is a key factor influencing the response of the coastal cells and the damage and recovery of the road network. The artificialisation of the coastal areas also turned out to be a factor locally affecting the impact of the hurricane. Urbanisation and the creation of a permanent shoreline and riverbanks amplified the destructive potential of the floods and swell for buildings and infrastructure by disrupting the mobility of hydraulic and sedimentary flows and accentuating erosion phenomena. This also had an effect on the recovery of highly urbanised sections of beach, where contrary to natural beaches, the absence of a stock of sediment above the beach did not allow significant local restitution of sediment in the medium term. The considerable damage done by Hurricane Maria is a telling indicator of the exposure and vulnerability of the island's population and infrastructure, which contributed to the disaster. Reducing and/or adapting the population and infrastructure in the most exposed areas (seafront, flood plain, steep slopes) and suitably rebuilding transport infrastructure should thus be prioritised with regard to the future development of Dominica and the expected intensification of hydrometeorological risks in the North Atlantic basin. In parallel, the improvement of non-structural and low-cost tools for mitigating risks such as prevention, warning, and evacuation,

redesigned for the ultra-local community scale, in particular on the coast, would be beneficial to supplementing the hazard-centred measures taken on the national scale.

Declarations

Funding: This work was supported by ANR's TIREX project (Grant number ANR-18-OURA-0002-05). Author S.B. has received research support from the University of Montpellier 3 Paul Valéry and MSH SUD.

Competing interests:

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions:

All authors contributed to the study conception and design. General material preparation, data collection and analysis were performed by Samuel Battut and Tony Rey. Rain and wind numerical modeling, mapping and analysis were performed by Raphael Cécé and Didier Bernard. Storm swell numerical modeling, mapping and analysis were performed by Yann Krien. Translation of the manuscript in english from french was performed by Semyon Kronrod. The first draft of the manuscript was written by Samuel Battut and Tony Rey and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Acknowledgements: The authors would like to thank the Department of Lands and Survey of the Ministry of Housing & Urban Development of Dominica for their collaboration and sharing of aerial imaging data, as well as the Climatological Department of the Dominica Meteorological Service for sharing available rain-gauge data. We would also like to thank Ian King, Program Manager for the United Nations Development Program in Dominica, who kindly agreed to discuss the assessment of building damage after the passage of the hurricane; Tangao Hu and Ronald B. Smith for sharing their updated map of land occupation in Dominica, used for the numerical modelling of the rain and wind gusts generated by Hurricane Maria; Yoland Jno Jules, chairman of the village council of Vieille Case, for sharing his knowledge of the roads and bridges on the west coast; and finally, all the Dominicans who generously agreed to share their knowledge and their experience of this major storm event, despite the painful memories evoked.

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Figures

Figure 1

Map of Dominica and location of study sites. Location of coral reefs and assemblages is modified from Steiner (2015). Map of land occupation from 2017 modified according to Hu and Smith (2018)

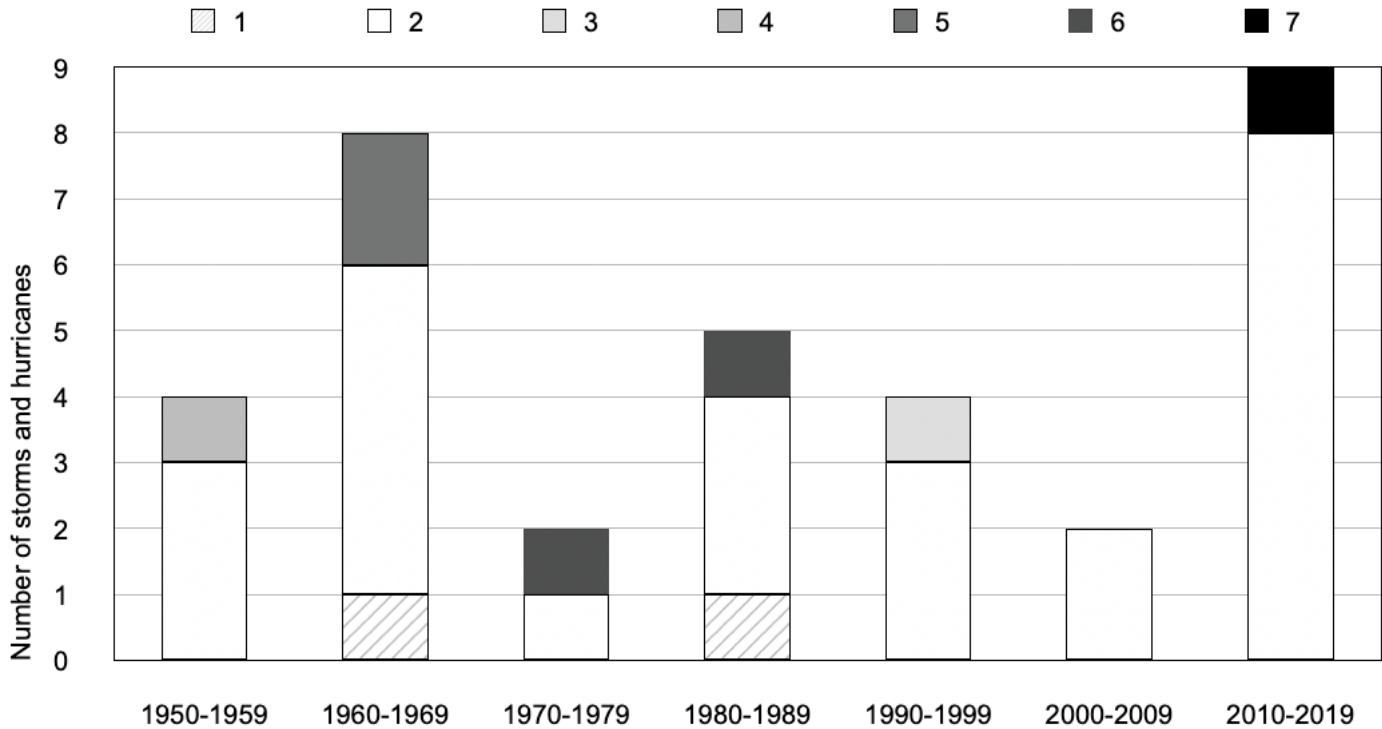


Figure 2

Number and intensity of depressions, tropical storms and hurricanes per decade between 1950 and 2019 with an eye that passed 100 km or less from Dominica. 1. Unnamed storm. 2. Tropical depression or storm (sustained winds of less than 118 km/h). 3. Category 1 hurricane (sustained winds between 119 and 153 km/h). 4. Category 2 hurricane (sustained winds between 154 and 177 km/h). 5. Category 3 hurricane (sustained winds between 178 and 210 km/h). 6. Category 4 hurricane (sustained winds between 211 and 251 km/h). 7. Category 5 hurricane (sustained winds of more than 251 km/h). The class of intensity for each storm depends on the wind speed reached at the point of the trajectory closest to the centroid of the island

Figure 3

Trajectory and characteristics of Hurricane Maria (16/09 - 02/10/2017) in the North Atlantic basin. Times are expressed in Coordinated Universal Time (UTC)



Figure 4

Overview of the 9 study sites: Portsmouth Bay (a), Colihaut (b), Number One Beach (c), Petite Savanne Bay (d) Mahaut (e), Fond Saint Jean (f), Pointe Mulâtre (g), Scotts Head (h), Grand Bay (i). The location of the sites is indicated in Fig. 1. The white line indicates the extent of the coastline studied for the monitoring of the changes in the shoreline

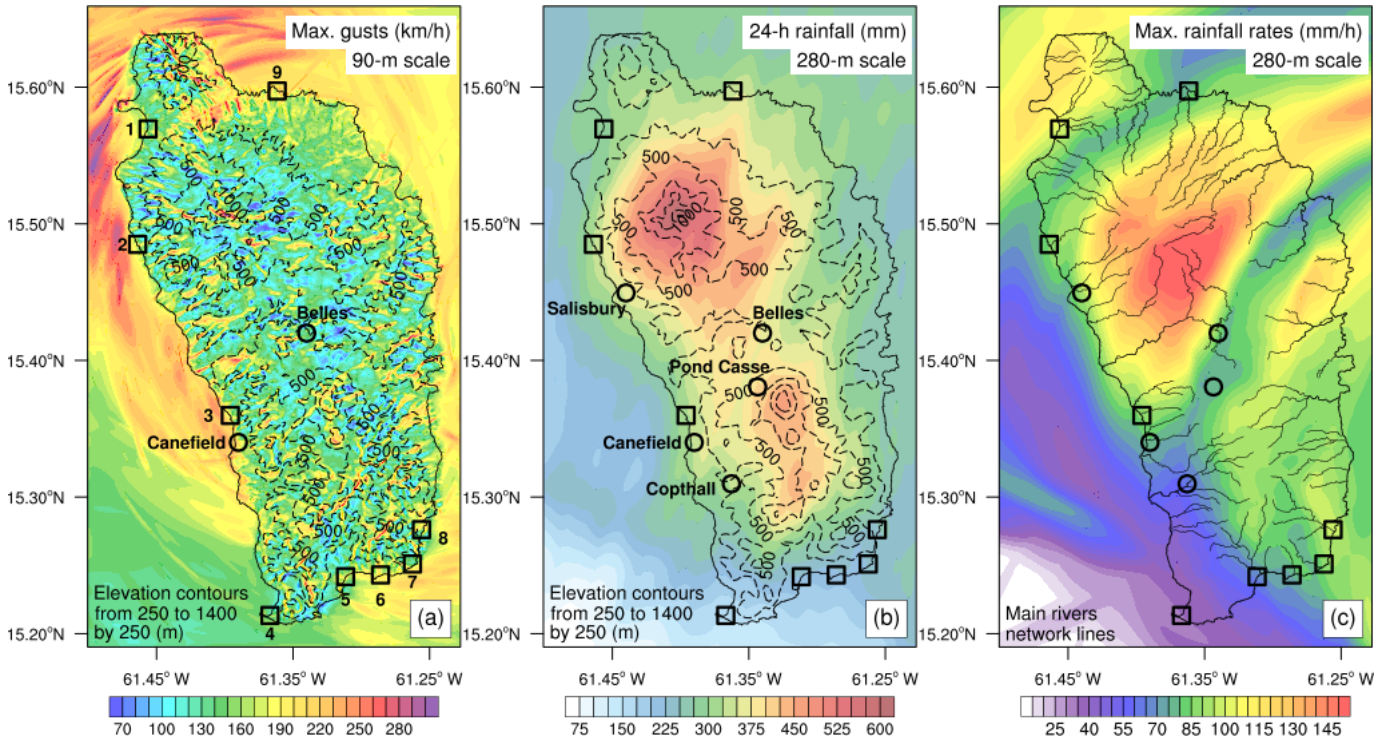


Figure 5
 Model results: maximum gust values in km/h at 90-m scale (a), 24-h accumulated rainfall in mm at 280-m scale (b), and maximum rainfall rates in mm/h at 280-m scale with the main river network (c)

Figure 6
 Maximum significant wave height and mean wave direction at the peak energy, computed by the numerical model (a) and maximum water level (relative to mean sea level) (b). The dashed white line represents the track of the hurricane

Figure 7
 Change in the position of the shoreline caused by the passage of Hurricane Maria in Grand Bay (a), Petite Savanne (b), Mahaut (c) and Portsmouth Bay (d)

Figure 8
 Change in the position of the shoreline in the post-storm period in Grand Bay (a), Petite Savanne (b), Mahaut (c) and Portsmouth Bay (d)

Figure 9
 Evidence of erosion and of transport of sedimentary materials towards the river mouths. Steep slopes and landslides above Petite Savanne (a). Ablation marks on the banks of the White River at Pointe Mulâtre (b). Voluminous heterometric deposits on the beach at Petite Savanne (c). Megablock transported by the flood and deposited at the mouth of the White River at Pointe Mulâtre (d). Battut, 2019

Figure 10

Hydrosedimentary morphological impact of Hurricane Maria. Overall flood extent (river and coastal flooding) in the village of Colihaut (a). Diachronic map of the mouth of the Geneva River in Grand Bay (b). Diachronic map of the mouth of the White River at Pointe Mulâtre (c).

Figure 11

Morpho-sedimentary impact of marine origin at Number One Beach : exposed root system of coconut trees (a), washover deposits with mats of *Ipomoea pes-caprae* (b), coral rubble deposited by waves (c), washed action on a seafront cliff (d), washover deposits and fallen coconut trees (e).

Figure 12

Impact of the storm swell on the various vertical surfaces of the seafront. Protective wall at Portsmouth Bay (Coconut Beach) (a), Retaining wall at Scotts Head (b), dune cliff at Pointe Mulâtre (c). Battut, 2019

Figure 13

Various types of damage to buildings associated with the passage of Hurricane Maria. Fluvial sediment deposits in Colihaut (a). Ground floor of a home submerged by the flood deposits in Colihaut (b). Home partly swept away by a flooded stream in Berekua, Grand Bay (c). Waterfront home partly swept away by the storm swell in Scotts Head (d). Rebar from the destroyed walls of a waterfront building bent by the storm swell in Scotts Head (e). Battut, 2019



Figure 14

Wave impact on Scotts Head seafront. Coarse deposits of marine origin on the pavement in Scotts Head (a). Coastal Road heavily damaged by the storm swell between Soufrière and Scotts Head (b). Photographs by Gemma Handy (BBC News 2017)

Figure 15

Recovery of road network and water-crossing structures in the aftermath of Hurricane Maria on the west coast of Dominica. Capuchin to Colihaut (a). Coulibistrie to Massacre (b). Canefield to Scotts Head (c). Road states refer to these 7 dates, in chronological order from the centre to the outside of the line: 25/09/2017, 28/09/2017, 03/10/2017, 04/11/2017, 24/11/2017, 12/01/2018 and 01/04/2019. Landslides that directly affected roads were detected using very-high-resolution orthophotography from October 2018

Figure 16

Relationship between the mean slope of the main rivers and catchment areas associated with each study site and the mean net shoreline movement (NSM)

Figure 17

Relationship between the damage level of assessed buildings and their roof materials (a) and size (b). Source: BDA

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