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Impact of Extreme Weather Events on the Beaches of Puerto Rico: The Case of Ocean Park, San Juan

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Abstract Extreme weather events (EWE) affecting the island of Puerto Rico have increased in frequency and intensity since 2010, including tropical cyclones, cold fronts, heat waves, etc. The most devastating of these events was Hurricane Maria (HM) in 2017, which caused estimated damages of more than $94 billion dollars and destroyed the coastline of the island [1]. After the hurricane, a series of extreme events has caused further erosion along the coastline, especially along the northern coast, which is eroded by the Atlantic Ocean. Ocean Park Beach is located along the northern coast in San Juan, which was greatly affected by coastal erosion during the summer of 2019 as a result of extreme events and increasing sea level. At the same time, due to the poor planning of coastal infrastructure, these events have severely impacted housing, commercial, and tourism infrastructure (restaurants, hotels, bars, etc.) as well as recreational activities such as beach volleyball, football, paddle surfing, windsurfing, etc.

Keywords: *coastal erosion, Puerto Rico, extreme events, Ocean Park*

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1. Introduction

Sun, sea, and sand tourism is one of the fastest growing activities in the Caribbean, especially in Puerto Rico (PR). The Caribbean coastline is a top destination for thousands of local and foreign tourists. However, over the last 10 years, as tourism activities have increased, coastal erosion has become a serious problem, increasing in both magnitude and frequency. Within this context, the present article analyzes the impact of an extreme event (tropical cyclones and cold fronts) on the northern coast of San Juan, PR. A brief analysis is presented for the resulting erosion event that impacted the beaches of Ocean Park.

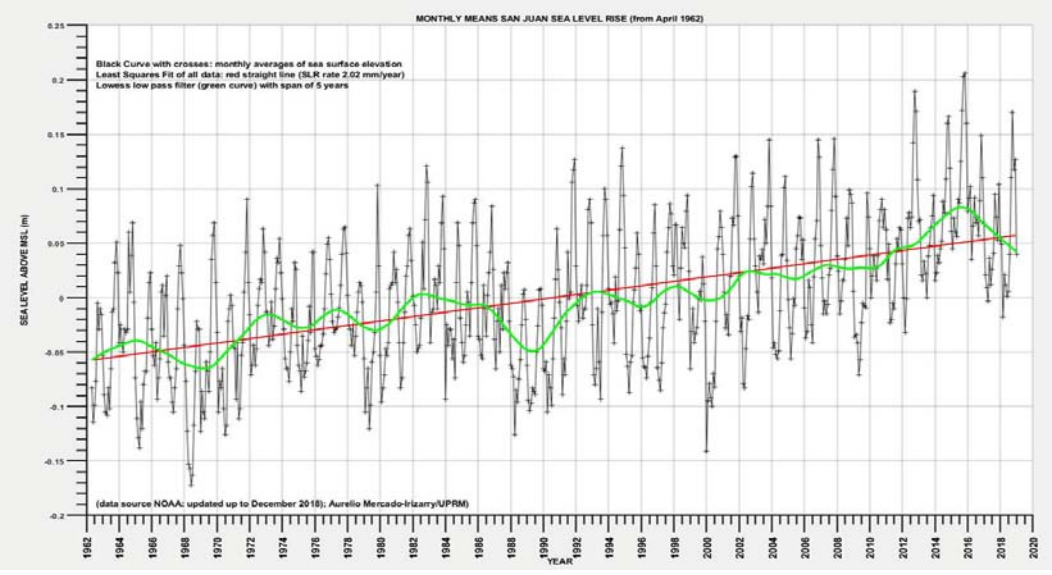

Figure 1. Behavior of sea level rise on the northern coast of Puerto Rico (Atlantic Ocean) from August 1962–2019. Source: Aurelio Mercado, University of Puerto Rico at Mayagüez

The behavior of beaches is complex, especially in the Caribbean, due to diverse geological, oceanographic, and meteorological variables that act simultaneously within a small geographical area [2,3]. Previous studies in PR have identified tropical cyclones as one of the main geological agents that has caused beach changes over the past four decades [4,5]. Since 2010, an increase in extreme weather events has been reported in the Caribbean [6], especially wave events resulting from winter storms (cold fronts) and hurricanes. Such extreme wave events have a more pronounced impact on erosion rates compared to normal wave patterns.

Scientific interest in climate changes and extreme events has substantially increased in recent years. Extreme weather events (EWEs) such as hurricanes, heat waves, and drought have disproportionate impacts compared to everyday weather [7,8]. Several studies [9-13] highlight the impact of EWEs on the coasts of the world's main oceans. In the case of PR, an evaluation was recently conducted to assess the state of the coast after the impact of Hurricane Maria (HM). The findings showed that erosional and depositional features are not evenly distributed along the coast; sediment deposition is more pronounced in some areas resulting in a wider beach. While other areas showed a more pronounced erosion [4].

Since 2010 the coastlines of PR have suffered an increase in the rate of erosion in many sites that has either been caused or exacerbated by the impact of various climatic phenomenon, such as tropical cyclones and large swells produced by cold fronts traveling from west to east across the Atlantic Ocean. Hurricanes Irma and Maria had a direct impact 2017, leaving the Puerto Rican coastline vulnerable and defenseless. It has also been impacted by climate change, including the increase of temperature, sea level (SL), and the magnitude and frequency of storms. For example, in the northern coast of PR the SL has risen 2.02 mm/year (Figure 1).

For HM, the impact on the southeastern region of PR was severe, affecting directly the municipality of Yabucoa. Because it passed through the municipality as a category 4 hurricane with winds of 250 km/h and a storm surge that exceeded 8 m. The hurricane remained over PR for 12 hours [1], causing 64 fatalities, although various studies have suggested that the figure could exceed 4,000 [14-18] in the aftermath of the hurricane given that communication and energy infrastructure suffered a total collapse for more than 3 months and, in some cases, up to 6 months following the hurricane. The economic losses exceeded $94 billion dollars, representing the most expensive hurricane in the United States and its territories. Along the coast, HM caused a loss of beach elevation in the majority of beaches. In addition, a loss of beach width was identified in many sites along the western-northwestern, northern central, and southeastern municipalities of the island. An increase in erosion was mainly observed in beaches with previous erosion history and/or with high levels of human intervention [4]. As a result, many coastal sites were left more physically vulnerable to future extreme events.

Erosion events caused by the precession of cold fronts and extratropical storms are frequent in the Caribbean, beginning at the end of October and beginning of November, what is commonly known as "Marejada de los Muertos" in Spanish (All Souls' Day or the Commemoration of All the Faithful Departed). This storm surge has increased its impact on the north and northeast coast of PR, due to the increase in the SLR for 2010 (Figure 1).

2. Impact of Coastal Erosion in San Juan

Ocean Park Beach is a beautiful beach conveniently located in the capital of Puerto Rico, San Juan, along the Atlantic coast near restaurants, residential apartments, hotels, and commercial stores. It is a sandy beach with a width exceeding 80 m in some places. Here, many water sports are practiced, and tourists and locals come to exercise or sunbathe. Several recreational activities are available, including beach volleyball to football, paddle surfing, windsurfing and many others.

According to the 2010 census, the Ocean Park sector had 1,667 inhabitants within an area of 0.52 km². It is located between the beaches of Condado and Isla Verde [19]. Most structures are single-family homes built between 1930 and 1950. There are also several hotels and bed and breakfast lodging establishments.

An initial field survey was done to identify the areas of major beach erosion for further monitoring (Figure 2 and Figure 3). Among the findings, we can highlight the presence of a vertical cut (microcliff) with a height of 2.4 m (Figure 4), the exposure of small lenses of beachrock in areas of former beach, the shift toward a concave beach profile, the exposure of previous informal mitigation structures, and sand loss (along an approximately 25-m long strip parallel to the coast). This microcliff was caused by strong wave activity, especially when waves with limited swash and stronger backwash withdraw sediments, cutting into the beach profile and leaving an erosional profile. Based on field observations, the swell coming from the northeast is also associated with the removal and transference of sediments to other areas of the coast. The stratigraphy of the beach was examined using 1.6 m of exposure (microcliff) (Figure 5 and Figure 6).

Figure 2. Impacted area the first week of August 2019. Source: Endi-JuxtposeJs

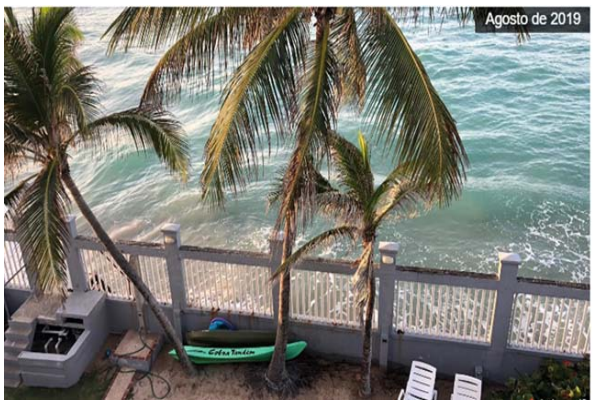

Figure 3. Impacted area during the third week of August 2019. Source: Endi-JuxtposeJs

Figure 4. Vertical cut produced by wave impact during the second week of August 2019. Source: Méndez-Tejeda

Figure 5. Microcliff or erosional cut (about 1.8 m high; Intervals every 10 cm). Source: Pérez-Valentín

Figure 6. Exposure of informal coastal mitigation structures (Jacob's staff with 10-cm intervals). These containers were used to fill in from 1930 to 1940. Later, constructions were built. Image: Pérez-Valentín

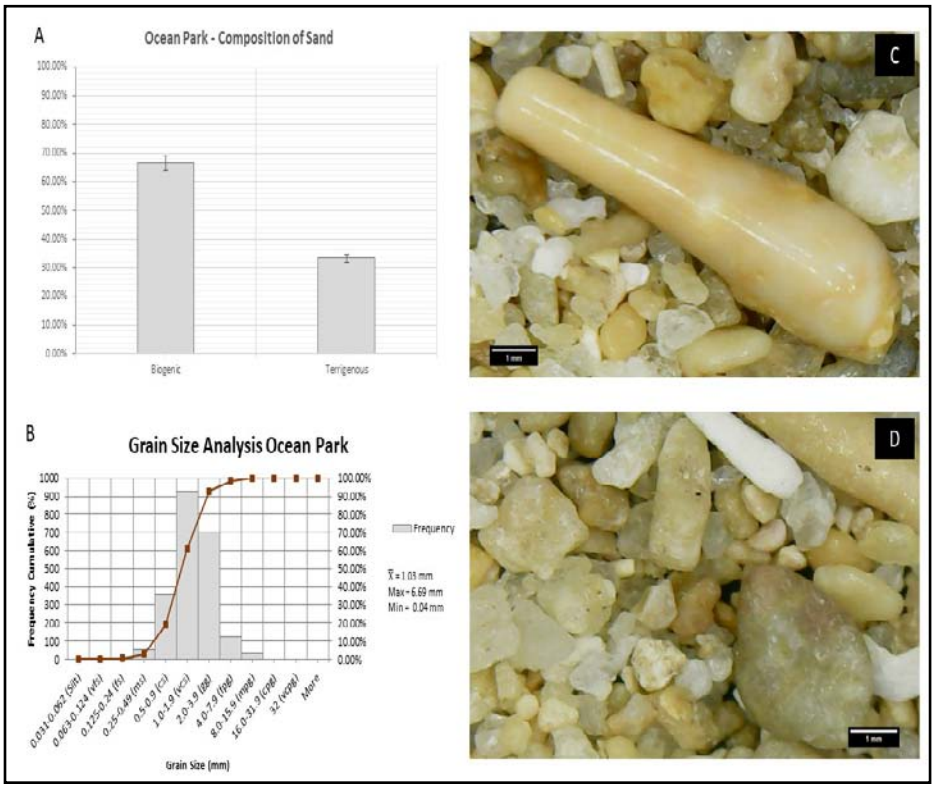

Figure 7. A) Graph of sand composition showing 66.65% biogenic components and 33.35% terrigenous material. B) Histogram of grain sizes (8/8/19). C and D) Photomicrographs of Ocean Park sand. Note the abundance of calcareous sand particles (echinoderm spine). Source: Pérez-Valentín

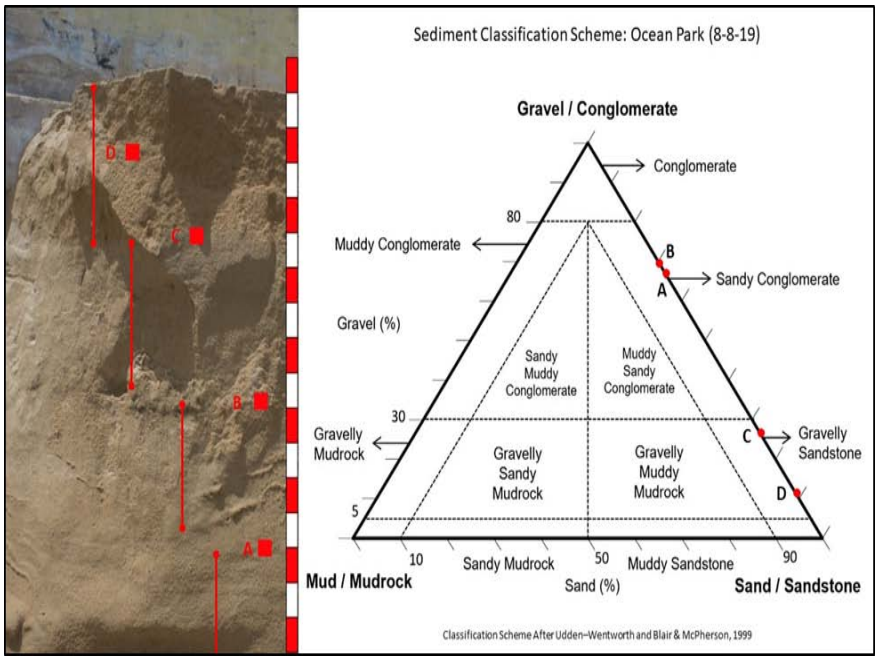

Figure 8. Image showing the four main sedimentary packages (also units) classified based on grain size (scale shows 10-cm intervals). Units A and B are unconsolidated sandy gravel (sG). Units C and D are classified as gravelly sand (gS). Units A-B and C-D share grain size characteristics but differ in composition and occurrence of sedimentary structures (e.g., cross bedding and planar bedding). Source: Pérez-Valentín

The sedimentology of Ocean Park Beach was examined to understand variations in grain size and spatial-temporal changes associated with beach erosion and depositional processes. The composition of the sediments was heterogeneous (of mixed origin), which is expected for this type of depositional environment. The current beach composition was dominated by biogenic calcareous clasts (66.65%) and terrigenous material (33.35%) (Figure 7). This composition suggests the contribution of fluvial sediments as terrigenous clasts (e.g., quartz, lithic fragments, and minor occurrence of magnetite) which appear to be incorporated with fragmented calcareous marine material (e.g., mollusk shells and disarticulated echinoderms) derived from the nearshore reef area (Figure 7 and Figure 8). In addition, the granulometric analysis revealed a wide range of grain sizes (from very fine sand to medium pebbles). In order to characterize coastal sediments, it is not adequate to examine grain size from a single sample or assume spatial uniformity [20]. Changes in granulometric distribution were documented not only in the microcliff area but also horizontally along the beach. Sedimentological parameters should be considered in the mitigation process of the coast. However, it is important to recognize the causes of coastal erosion are not only limited to changes in currents or wave activity but are multifactorial and require detailed study. This beach and its sands serve as a refuge for dozens of Leatherback sea turtles (*Dermochelys coriacea*) that arrive every year to lay their eggs, which then hatch along the beach.

Erosion events were also identified at other coastal sites such as Barrio Obrero at Arecibo, Fortuna at Luquillo, Villa Cristiana and Parcelas Suarez at Loiza, and Corcega and Barrero at Rincon, among other sites. These events have caused a loss of infrastructure and natural habitat for marine species and an increase in both the social and physical vulnerability of local communities. For this reason, it is urgent for state and federal governments to provide solutions to mitigate the impacts of erosion on these communities and touristic areas, which is one of the main sources of income in PR [21].

3. Analysis and Conclusions

Erosion at Ocean Park Beach has been aggravated by EWE and sea level rise. However, erosion might also be seen as the result of decades of coastal mismanagement. The Ocean Park area once formed part of a wetland (see Figure 8) that was eventually subtracted from the sea. Accordingly, the constructions built in the area have violated the land-maritime zone.

Although some beaches recover after a period of erosion, they do not return to their initial state. Also, once beaches are eroded, they become more vulnerable to extreme weather events and may continue to lose sand. The presence of hard structures (breakwaters, walls, houses, etc.) can further exacerbate this phenomenon, of which Ocean Park is an excellent example.

Unfortunately, hard coastal infrastructure intended to protect the coastline has been in several cases to be more of a problem than a solution (Rangel-Buitrago et al. 2015) [21], as the implementation of hard structures as protection measures against coastal erosion has generally resulted in negative impacts. Direct and indirect experience indicates that optimal results in terms of time and money invested can be reached by a combination of different hard and soft solutions. Soft engineering measures should be prioritized because of their ability to work in harmony with nature.

Finally, it is important that decision makers recognize that the management of the coastal zone is important not only as an economic and social resource but as an invaluable environmental resource that is essential for the sustainable development of Puerto Rico.

Acknowledgements

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