# NUMERICAL MODELING TO EVALUATE THE EFFECTS OF HURRICANE-INDUCED WAVES AND WATER LEVELS ON COASTAL DUNES ALONG THE NORTH COAST OF PUERTO RICO



**Project Title:** Strengthen Resilience from Extreme Weather through Ecological Restoration of Sand Dunes (PR)
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## 1. PROJECT SUMMARY

Two powerful Category 5 storms during the 2017 Atlantic hurricane season, hurricanes Irma and María, caused severe damage on most of the coastal sand dunes on the north coast of Puerto Rico. Many of the dunes were severely breached and some were totally flattened at several places due to a combination of wave attack and storm surge (Fig. 1). This resulted in inland inundations several hundred meters from the frontal seaside strip of the dunes in some areas adjacent to densely populated areas that include critical infrastructure. It is well known that coastal sand dunes play an integral role in coastal hazard mitigation and their restoration promotes the accumulation of higher volumes of sediment and increased percent vegetation cover that prevent further erosion and can attenuate strong wave energy. Restoring coastal dunes would result in an increase in the resilience of coastal communities and their vital infrastructure (Sutton-Greir et. al., 2018).

The potential vulnerability of a particular stretch of coast with and without coastal sand dunes can be assess using a numerical (mathematical) model that can replicate the local hydrodynamic conditions. This work describes the effects of hurricane-induced waves and water levels on coastal dunes from selected sites along the north coast of Puerto Rico using a numerical model to demonstrate their important role of providing a natural defense against flooding and wave attack.

Fig. 1 Breaching of coastal dunes by waves and storm surges.

## 2. PROBLEM STATEMENT

Storm activity from the hurricanes and cold-front systems since the 2017 Atlantic hurricane season has exacerbated the severe erosion along the coasts of Puerto Rico. Dunes are one of the first lines of defense for human communities and critical infrastructure (i.e., main access roads, sanitary infrastructure) against powerful storms, coastal erosion and flood hazards that impact human communities and local economies (Sigren et. al., 2018). In Puerto Rico, sand dunes are present in 13 municipalities on the north coast. Approximately 48% of those dunes are found in the municipalities of Isabela, Dorado and Loíza. Most of the dunes and beaches on the north coast of the island are severely eroded and some completely washed out by the combined action of storm surge and waves. The coastal dunes in Puerto Rico are currently in a very fragile state and have many other conservation threats (Fig. 2). These breaches to Puerto Rico's natural coastal defense not only impacted the natural ecosystems and living human communities, but also severely damaged the coastal archaeological sites that are located under and within the dunes, and which are part of Puerto Rico's cultural heritage (Rivera-Collazo 2019). Through Puerto Rican history and prehistory, these dunes and coastal ecosystems have been an integral part of the daily life of local communities. Today, the sand dunes protect hundreds of archaeological sites and other historically important remains.


Fig. 2 Threats to coastal sand dunes

The coastal sites where major dune erosion occurred are shown in Fig. 3 and include Isabela, Camuy, Hatillo, Arecibo, Manatí, Dorado, San Juan, Loíza, and Fajardo. All these coastal sites are located in municipalities declared major disaster (DR-4339) on September 20, 2017 after the impact of Hurricane María. These coastal sites are dominated by steady wind seas produced by easterly trade winds and by swell events caused by tropical storms, hurricanes, and North Atlantic winter storms. Tides are mostly semi-diurnal and have a small mean oceanic tidal range of 0.34 m. Sediment composition is comprised of fine to medium-fine quartz sand, although there is now a considerable amount of shell detritus in many sites.

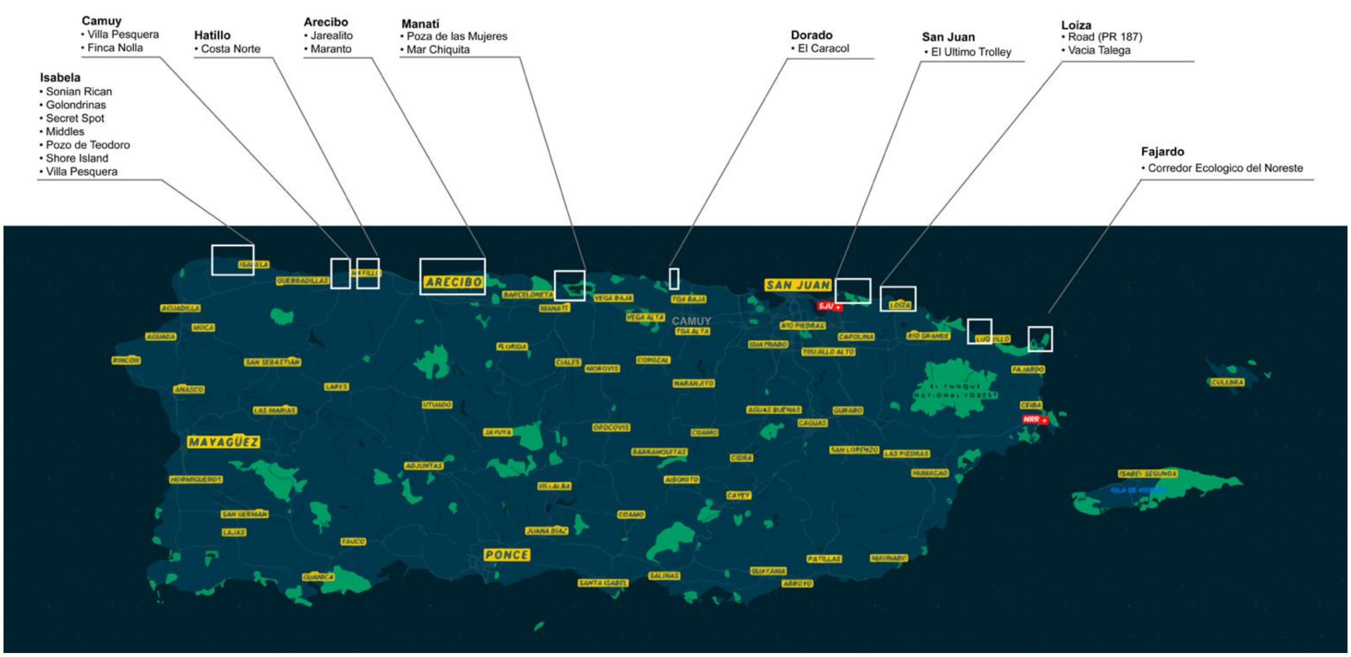


Fig. 3 Selected coastal sites along the north coast of Puerto Rico.

The dune systems, while protective, can be quite vulnerable to storm-surge, swash run-up, and highly energetic waves, especially along sections that are at lower elevation or discontinuous (Sallenger, 2000). The breaching of the dunes increases the risk of overwash causing damage to nearby critical infrastructure (i.e., main roads, water distribution systems, airports, among others;), habitats, and communities by flooding, scouring, and wave attack. Coastal infrastructure near low-elevation dunes is susceptible to such storm activity from both hurricanes and cold-front system (Dingler and Reiss, 1990; Stone et al., 2005).

An analysis of dune morphology changes derived from airborne LiDAR data, collected by the US Army Corps of Engineers in 2016 and 2018, exhibit a considerable degree of variability within some of the selected sites. Dune elevation fluctuated from erosion to accretion between sites depending on the shoreline orientation and the oceanographic conditions encountered during the storm activity. Fig. 4 shows the morphology (elevation) change map (*dz)* from the selected sites. Blue colors (or light areas) indicate erosion whereas red colors (or dark areas) indicate deposition. The subaerial portion of the stretch of coasts experienced more erosion ($dz < -0.5$ m), in other words, the pre-storm elevation/volume of the coastal dunes was lost. This implies that much of the sediment in the dunes along the north coast was lost offshore. The maximum erosion ($dz < -1$ m) in each site can be ascribed to the shoreline orientation with respect to the incoming storm waves. The opposite sides experienced deposition ($dz > 0$ m). However, no selected site maintained their original morphology after the impact of the storm events.

Maintain intact coastal sand dunes, helps shield nearby communities from the impact of storm surge and high waves. The potential vulnerability of a particular stretch of coast with and without coastal sand dunes can be assess using a numerical (mathematical) model that can replicate the local hydrodynamic conditions. This work describes the effects of hurricane-induced waves and water levels on coastal dunes from selected sites along the north coast of Puerto Rico using a numerical model to demonstrate their important role of providing a natural defense against flooding and wave attack.

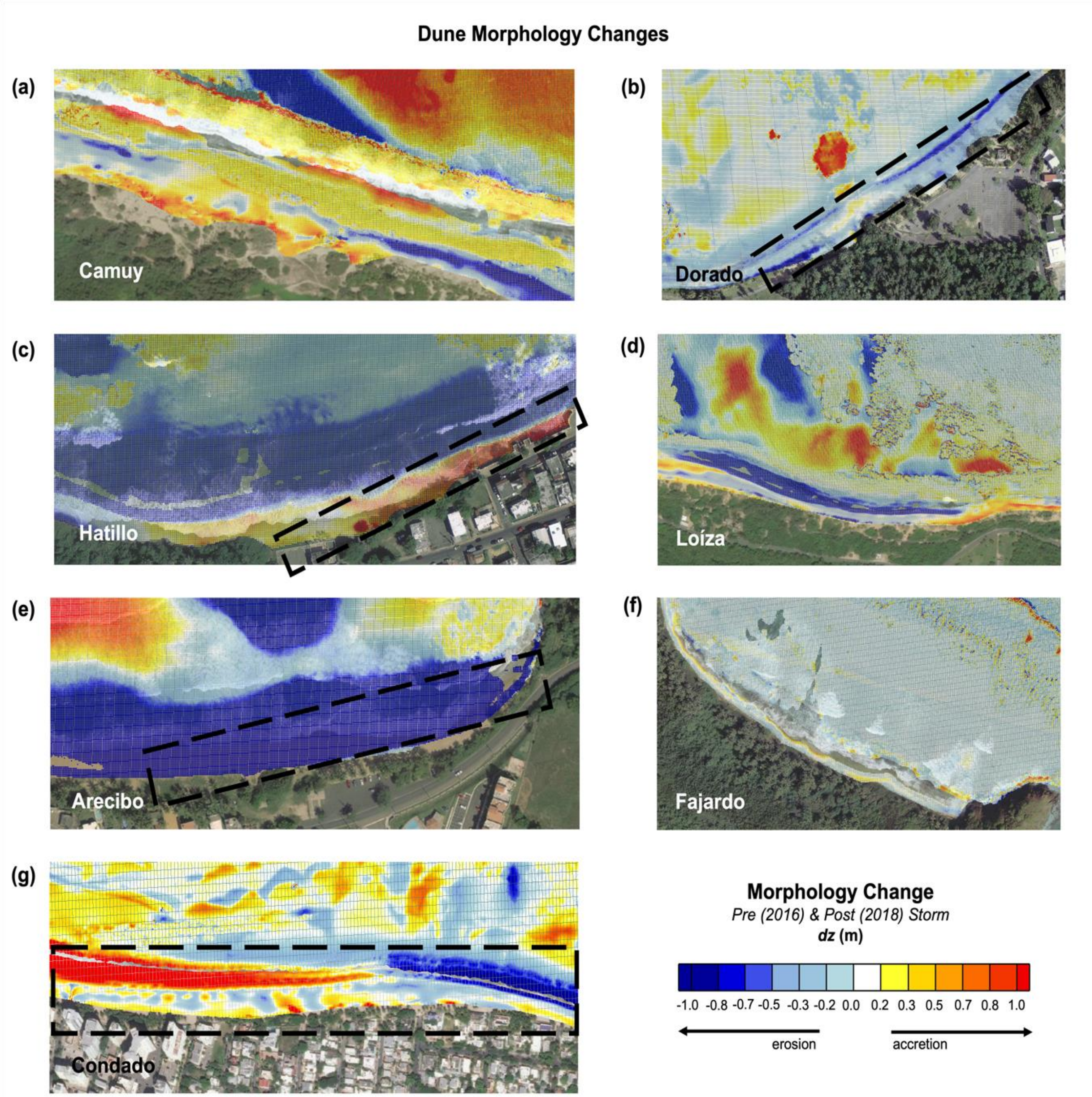


Fig. 4 Morphology change maps for selected sites estimated using LiDAR data collected in 2016 and 2018. Blue colors (or light areas) indicate erosion whereas red colors (or dark areas) indicate deposition

## 3. HIGH-RESOLUTION NEARSHORE WAVE MODELING

During tropical storms and hurricanes, coastal dunes are vulnerable to the impact of large storm surge and strong wave forces/attack. Modeling these nonlinear nearshore wave processes requires an efficient and accurate highly nonlinear time-dependent surface wave field model. The fully nonlinear, phase-resolving, time-stepping Boussinesq model, FUNWAVE (Shi et al., 2012), was used to accurately simulate wave propagation in the nearshore and predict wave transformation processes which comprise shoaling, refraction, diffraction, wave breaking, friction, etc. over irregular bathymetry, wave-structure interaction, and wave-induced circulation, among other nearshore processes from deep water to the foreshore.

### 3.1. Model setup

An offline approach was used to accurately simulate the wave transformation from offshore/deep water to the nearshore/shallow water. Two numerical cartesian grids were developed. The dimensions are approximately 3.9 km x 4.2 km for the two-dimensional grid and 3 km for the one-dimensional grid. The resolution of the two-dimensional grid was configured with grid cells of size 10 x 10 m and consisted of 292,929 grid cells. The one-dimensional grid was configured with grid cells of size 0.30 m and consisted of 9,843 grid cells. The Digital Elevation Model (DEM) data and bathymetry datasets were obtained from the Continuously Updated Digital Elevation Model (CUDEM) developed by NOAA's National Centers for Environmental Information (NCEI; https://coast.noaa.gov/).

Three types of boundaries were used in the model: (1) seaward boundary (wavemaker); (2) lateral boundaries (sponge layers); and (3) landward boundary. The model was driven by incident waves coming from an internal wavemaker located along the south boundary. The irregular nature of wave typical conditions in a nearshore zone, particularly during extreme events, were replicated using the JONSWAP spectrum wavemaker. The input parameters on the seaward boundary included significant wave height, peak wave period, mean direction, storm surge (water level) and wind speed. The water level boundary conditions that were provided to the phase-resolving model only took into account wind and pressure setup, not wave effects. The wind was included to consider the wind-wave generation. Since the area is small, the wind field was assumed to be spatially and temporarily constant. The wind speed replicated a Category 5 storm with wind speeds of more than 157 mph.

### 3.2. Boundary Conditions

#### 3.2.1. Wave Conditions

Hurricane Maria, a powerful Category 5 storm (downgraded to a Category 4 at landfall), struck the island of Puerto Rico on September 20, 2017, inducing strong mete-ocean conditions and causing widespread erosion. Offshore and nearshore wave conditions were measured by CARICOOS San Juan wave data buoy and simulated by CARICOOS Wave Forecasting Model (Fig. 5). The extreme event generated waves of up to 13 m. Maria had maximum wind gust of 47 m $s^{-1}$ and sustained wind of 17 m $s^{-1}$ at 10 m above ground.

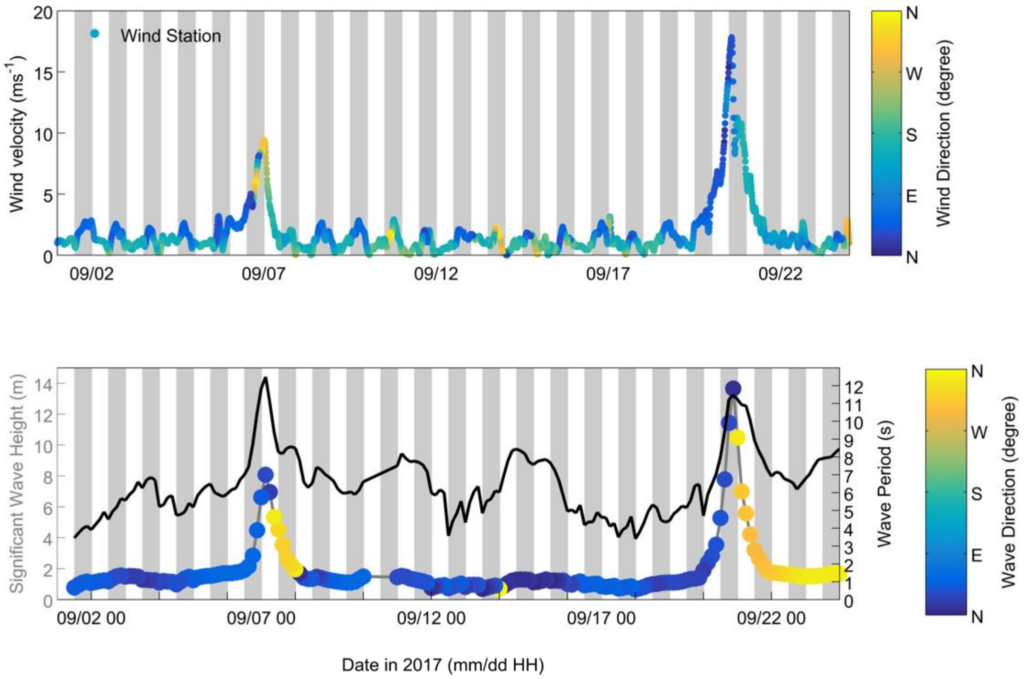


Fig. 5 Wave and wind conditions during Hurricane Maria (left column) and Winter Storm Riley (right column) in Isabela: (top row) sustained wind speed and direction (nearby wind station); (middle row) significant wave height (CARICOOS Wave Model), wave period and wave direction; (bottom row) water surface elevation. Gray shading in all panels indicate measurements during nighttime.

### 3.2.2. Water Levels

To appropriately simulate wave transformation in the vicinity of the project site, appropriate water level boundary conditions must be provided to the nonlinear, phase-resolving model in addition to the wave boundary conditions. Because probabilistic storm surge modeling was out of the scope of this study, existing datasets and previous modeling studies were reviewed to determine reasonable values for water level boundary conditions for the phase-resolving model.

### 3.2.3. Base flood elevation

FEMA's base flood elevation (BFE) maps, developed in 2018 based on a post-Hurricane María flooding study, were analyzed for the project site. Flood elevations in VE zone include both flooding levels and wave heights, making it impossible to interpret the individual contributions of water levels and actual wave heights. As a result, it is not possible to use FEMA's BFE levels for the boundary conditions of the high-resolution wave modeling needed to understand the dynamic processes near the selected sites.

### 3.2.4. Extreme water levels

The storm surge atlas for Puerto Rico developed by Prof. Aurelio Mercado (https://coastalhazardspr.wordpress.com), a physical oceanographer at the University of Puerto Rico-Mayaguez, was used to estimate extreme water levels for use as boundary conditions for simulating the 100-year and 50-year events. Such atlas was developed using the ADCIRC-pUnSWAN numerical modeling package to simulate a large number of synthetic hurricanes from categories 1 through 5 and from a range of angles of attack (Benitez & Mercado, 2015).

Maps of the Maximum of Maximum (MoM) storm surge elevations were analyzed for the project site and the maximum elevations outside of the surf zone were estimated as follows:

- Category 5 hurricanes: 1.30 m above MHW
- Category 4 hurricanes: 1.10 m above MHW

In the absence of a direct relationship between hurricane categories and recurrence intervals, the Category 5 and Category 4 maximum water levels were used as the boundary conditions for simulating the 100-year and 50-year storm events, respectively (Fig. 6). These values do not consider sea level rise.

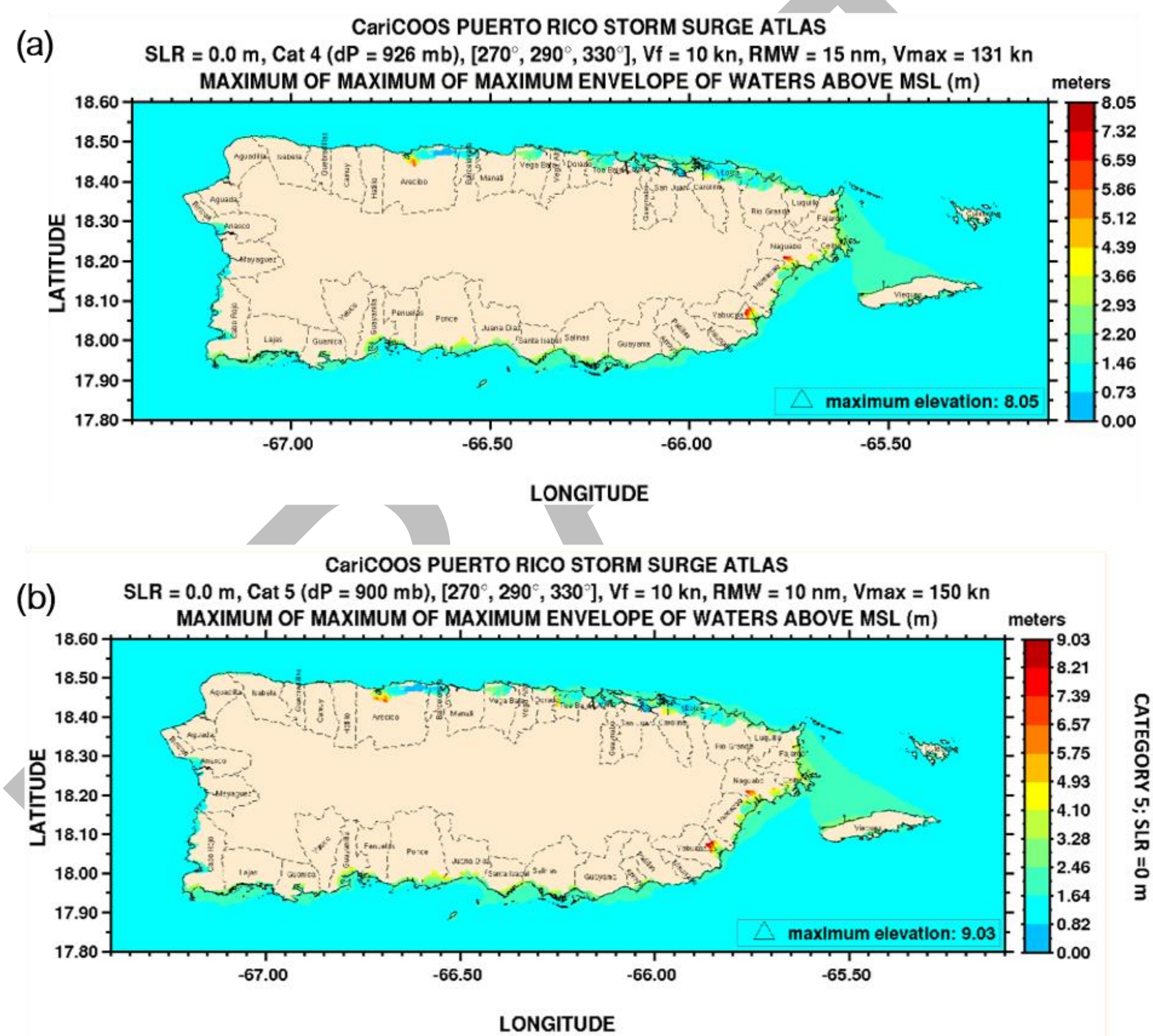


Fig. 6 Example of maps of maximum water levels for Puerto Rico considering a (a) Category 4 hurricane and a (b) Category 5 hurricane. These maps were developed for the CARICOOS Puerto Rico Storm Surge Atlas (Benitez & Mercado, 2015).

## 4. EFFECTS OF HURRICANE-INDUCED WAVES AND WATER LEVELS ON COASTAL DUNES

### 4.1. Two-dimensional simulations

A spatial analysis was conducted to study the spatial pattern of the wave field in the study area. High-energy wave conditions were generated for all selected sites. Fig. 7 shows an example of the spatial pattern of the significant wave height and water surface elevations. According to Fig. 7, significant wave height and water surface elevation are quasi-parallel, but as the wave field approaches the shore, the water fields become complicated and disordered. This behavior can be explained in terms of wave shoaling and refraction. The significant wave height reduced rapidly from offshore to shore within a short distance of about 1.0 km. When waves passed through the fringing reefs and other features (Fig. 7), shadows appeared in both wave height and water surface elevations near the onshore side of the reef foundation. This alters the wave energy and changes the wave properties (wave height, period, and direction).

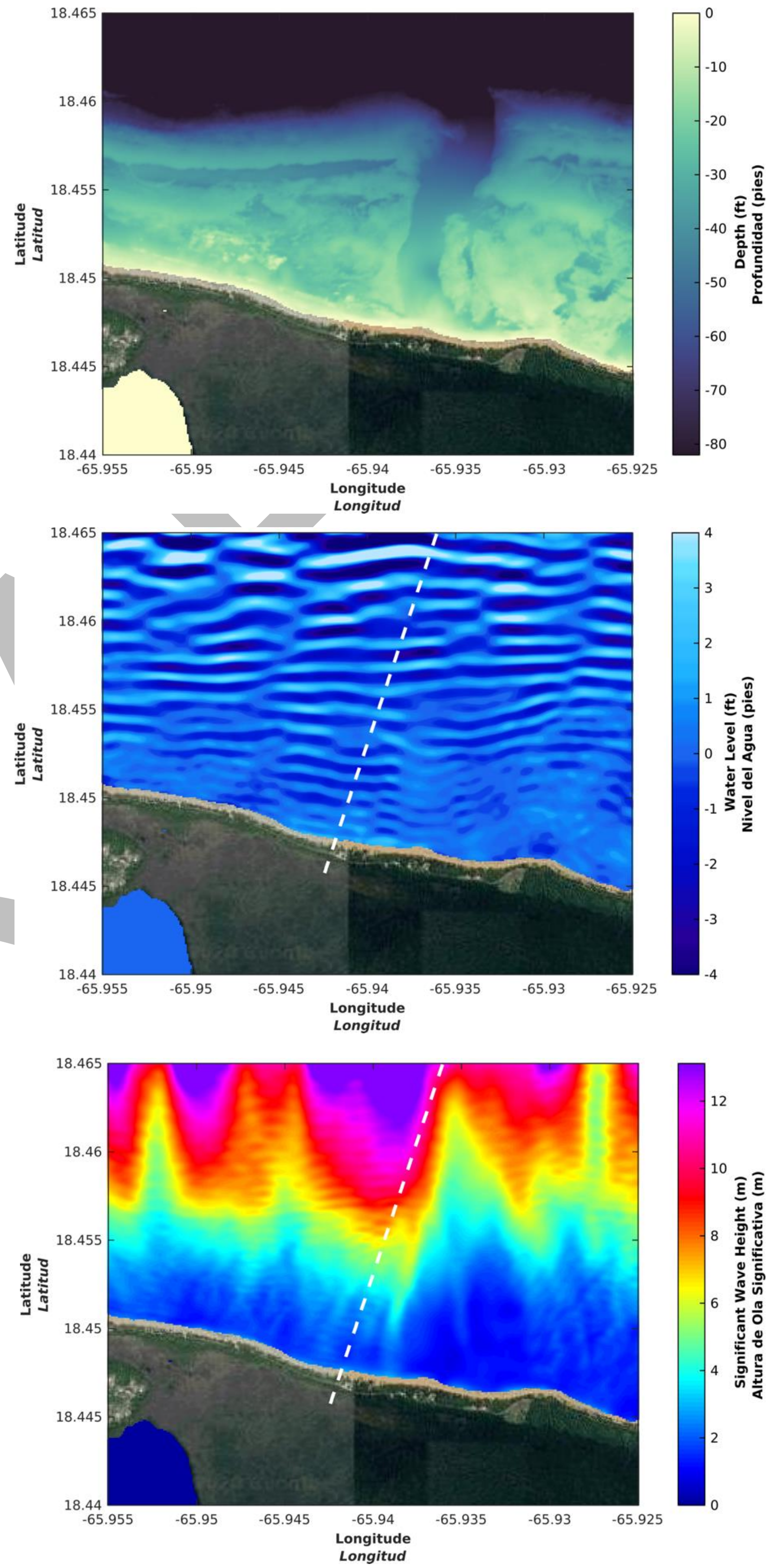


Fig. 8 An example of the (top panel) bathymetry, (middle panel) water surface elevation, and (bottom panel) water surface elevation fields in Loíza for maximum conditions generated by Hurricane María.

### 4.2. One-dimensional simulations

This section focuses on the analysis of the computed one-dimensional storm-induced hydrodynamic conditions for the selected sites. Fig. 9Fig. 24 show a beach elevation transect for the coastal site with (pre-storm conditions) and without (post-storm conditions) coastal dune. The elevation profile before Hurricane Maria from the 2016 USACE NCMP Topobathy Lidar (Fig. 9Fig. 24 top panel) and after the hurricane based on imagery (Fig. 9Fig. 24 bottom panel). As mentioned before, the dunes during Maria held back the rise of the water levels, protecting the inland structures from flooding. However, after Hurricane Maria most of the coastal dunes did not recover nor were restored. Therefore, coastal sites without dune will allow inland inundation of approximately 250 to 300 m from the foreshore. The simple analysis shows that water can reach the dune during highly energetic conditions potentially inducing erosion (Fig. 6). However, the dense vegetation stabilizing the sandy dunes played an integral role in coastal hazard mitigation strategies protecting the dunes from severe erosion. The numerical simulations confirmed that stabilized coastal dunes could protect nearby critical infrastructure and reduce damages from severe storm surge. The numerical simulations also indicated that the extent of the coastal/nearshore zones play an integral role in coastal hazard mitigation strategies and confirms that with larger volume of sediment and a wide beach, the coast will take longer to erode and will attenuate more wave energy.

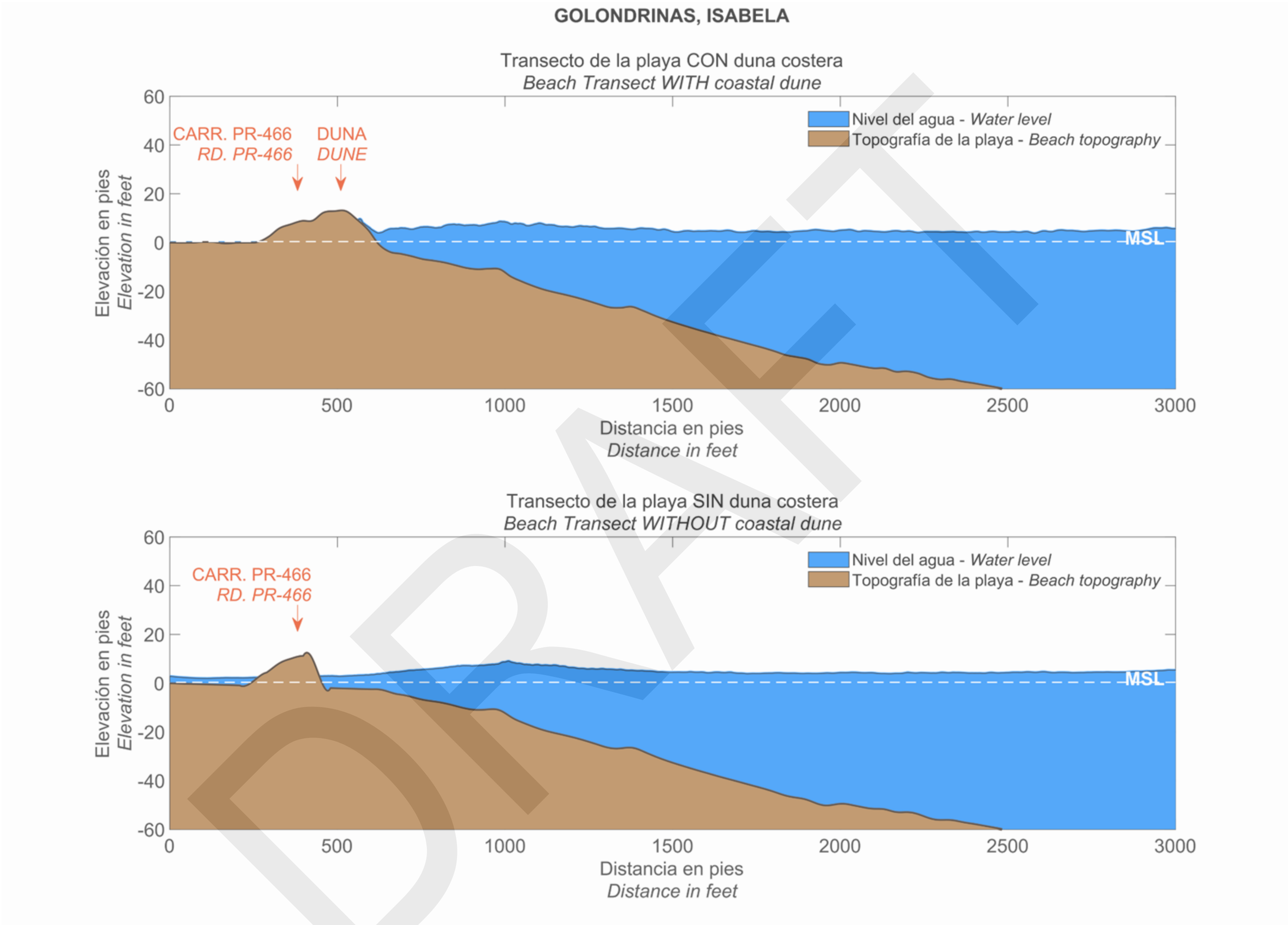




Fig. 9 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Golondrinas, Isabela. Horizontal gray line denotes the mean sea level.

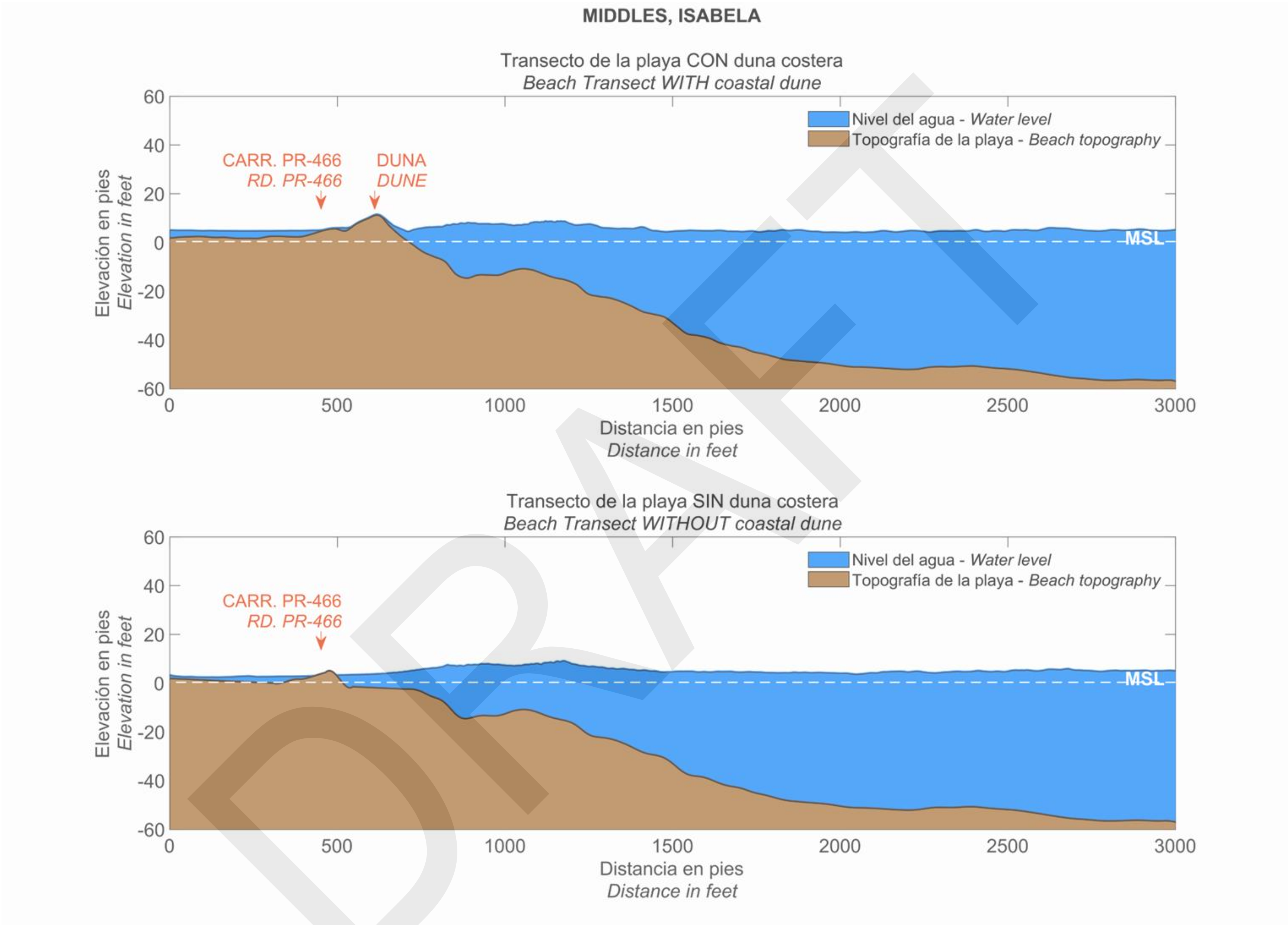


Fig. 10 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Middles, Isabela. Horizontal gray line denotes the mean sea level.

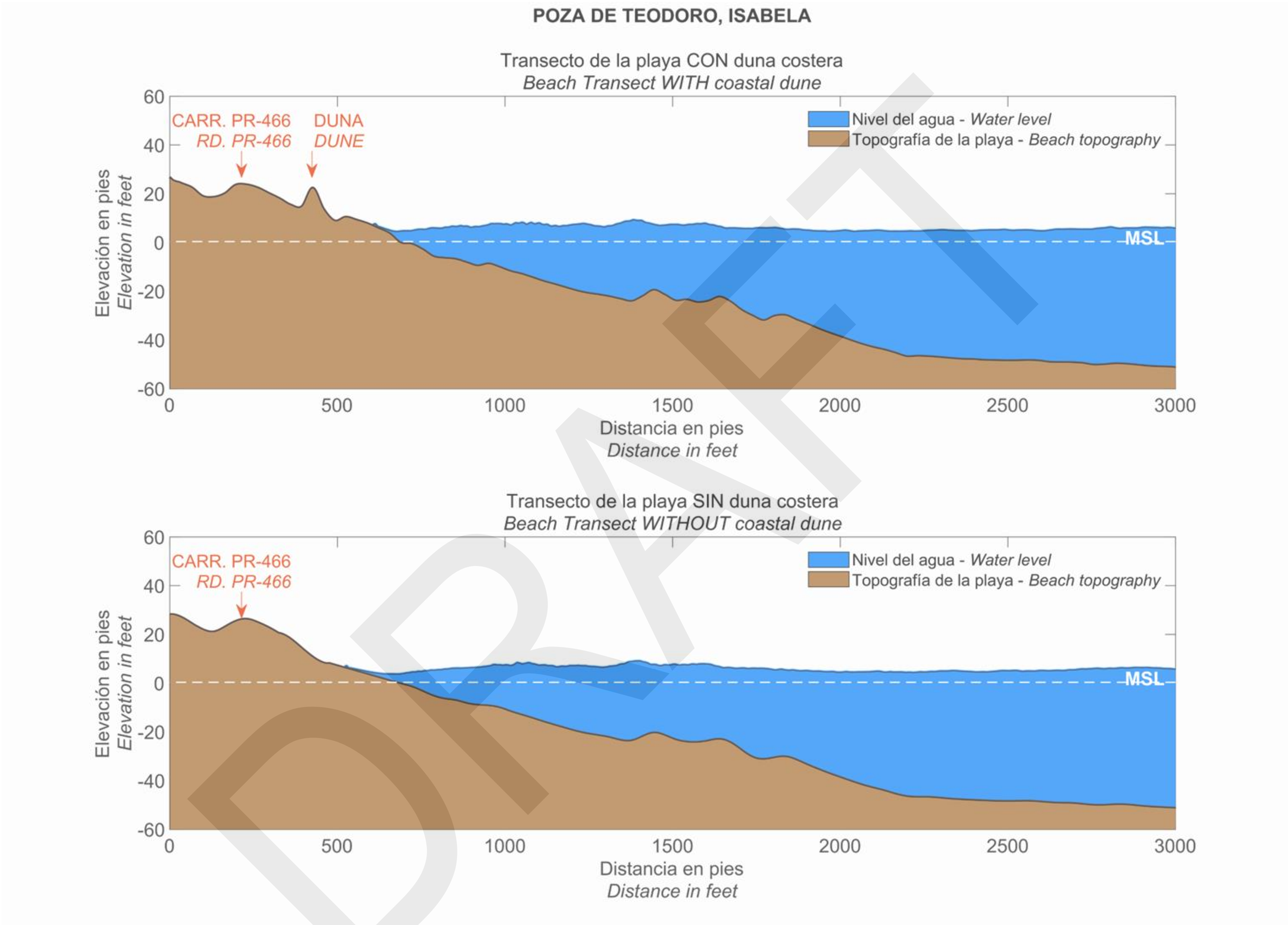




Fig. 11 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Poza de Teodoro, Isabela. Horizontal gray line denotes the mean sea level.

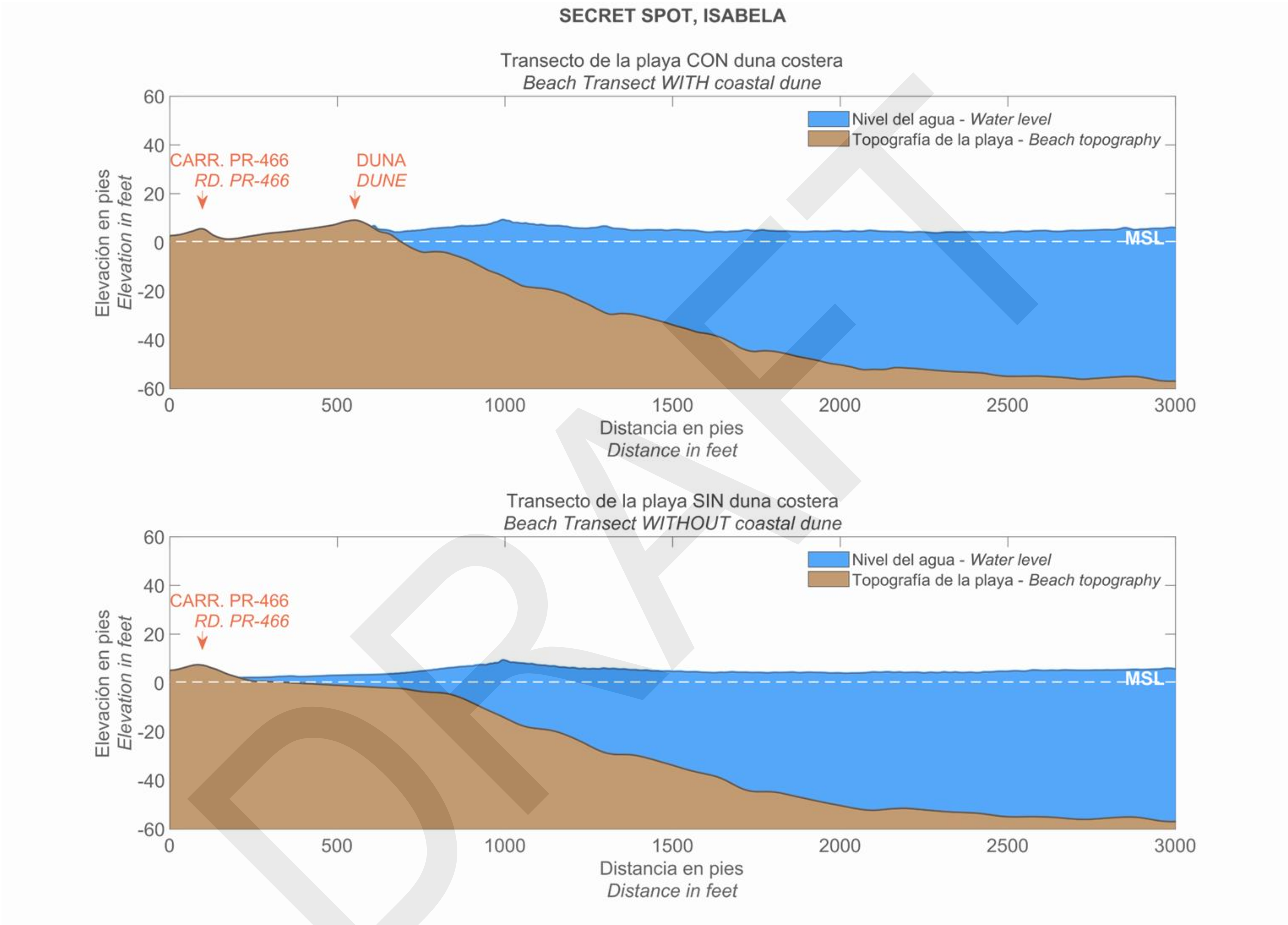


Fig. 12 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Secret Spot, Isabela. Horizontal gray line denotes the mean sea level.

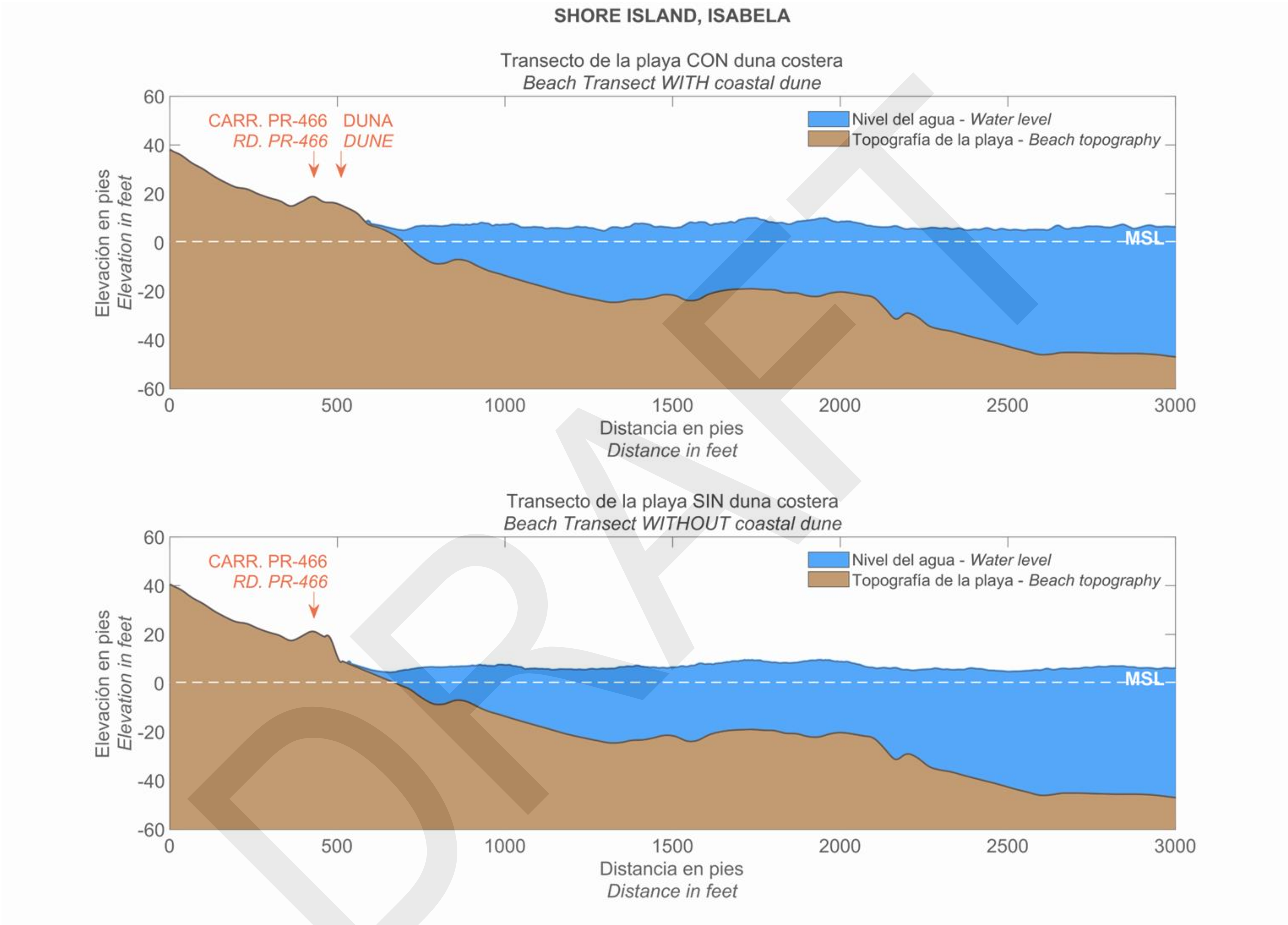


Fig. 13 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Shore Island, Isabela. Horizontal gray line denotes the mean sea level.

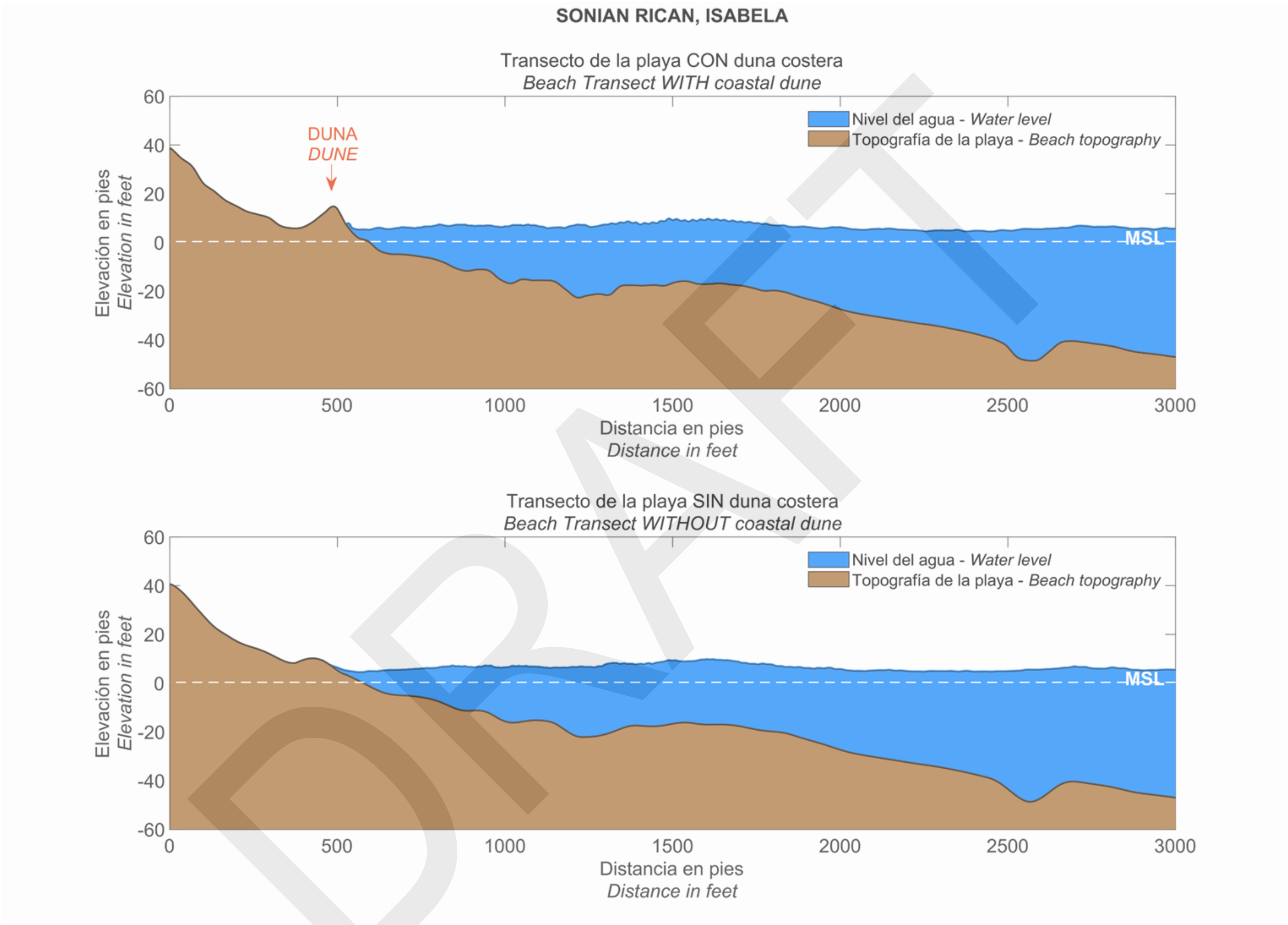


Fig. 14 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Sonian Rican, Isabela. Horizontal gray line denotes the mean sea level.

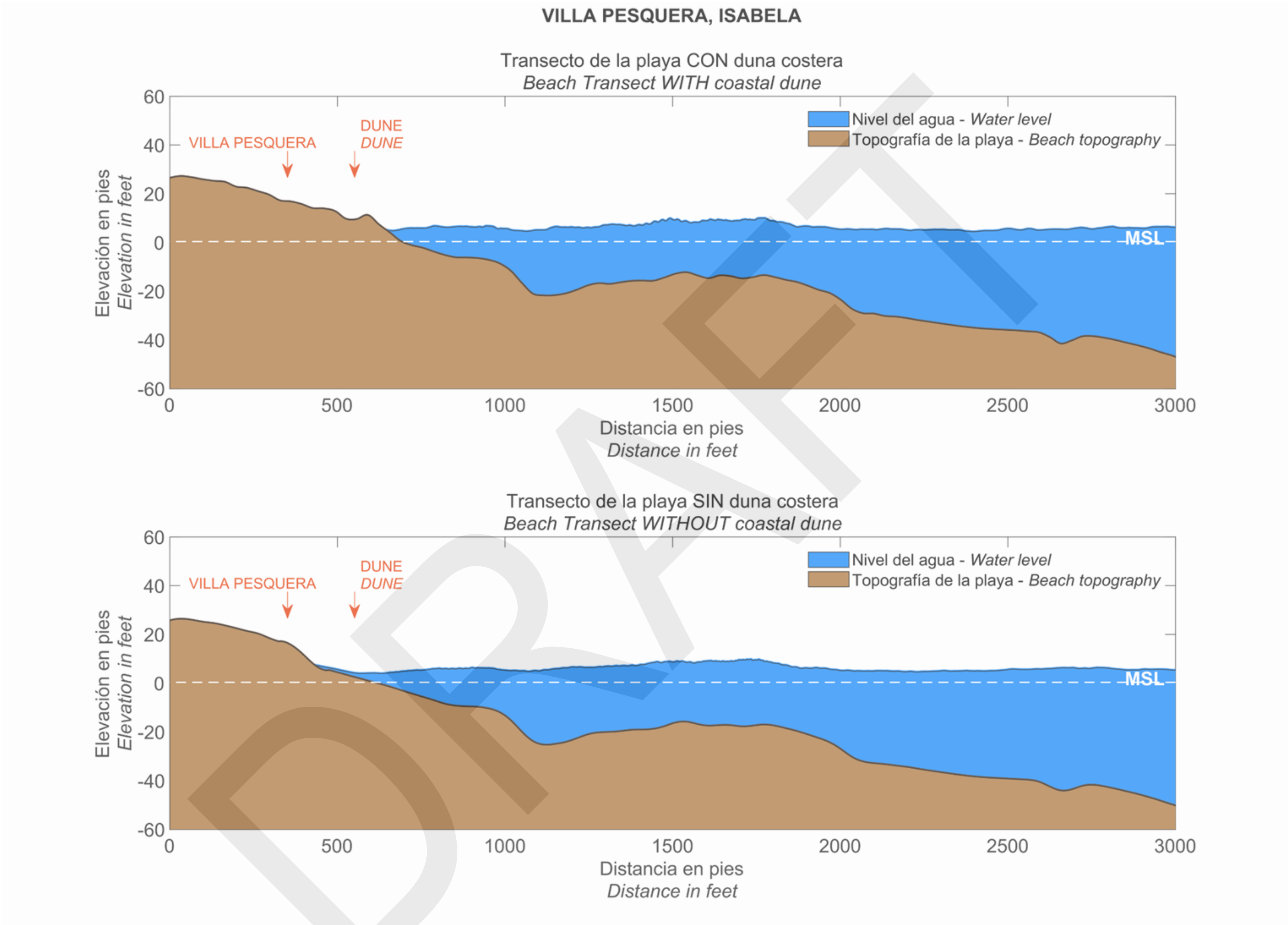


Fig. 15 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Villa Pesquera, Isabela. Horizontal gray line denotes the mean sea level.

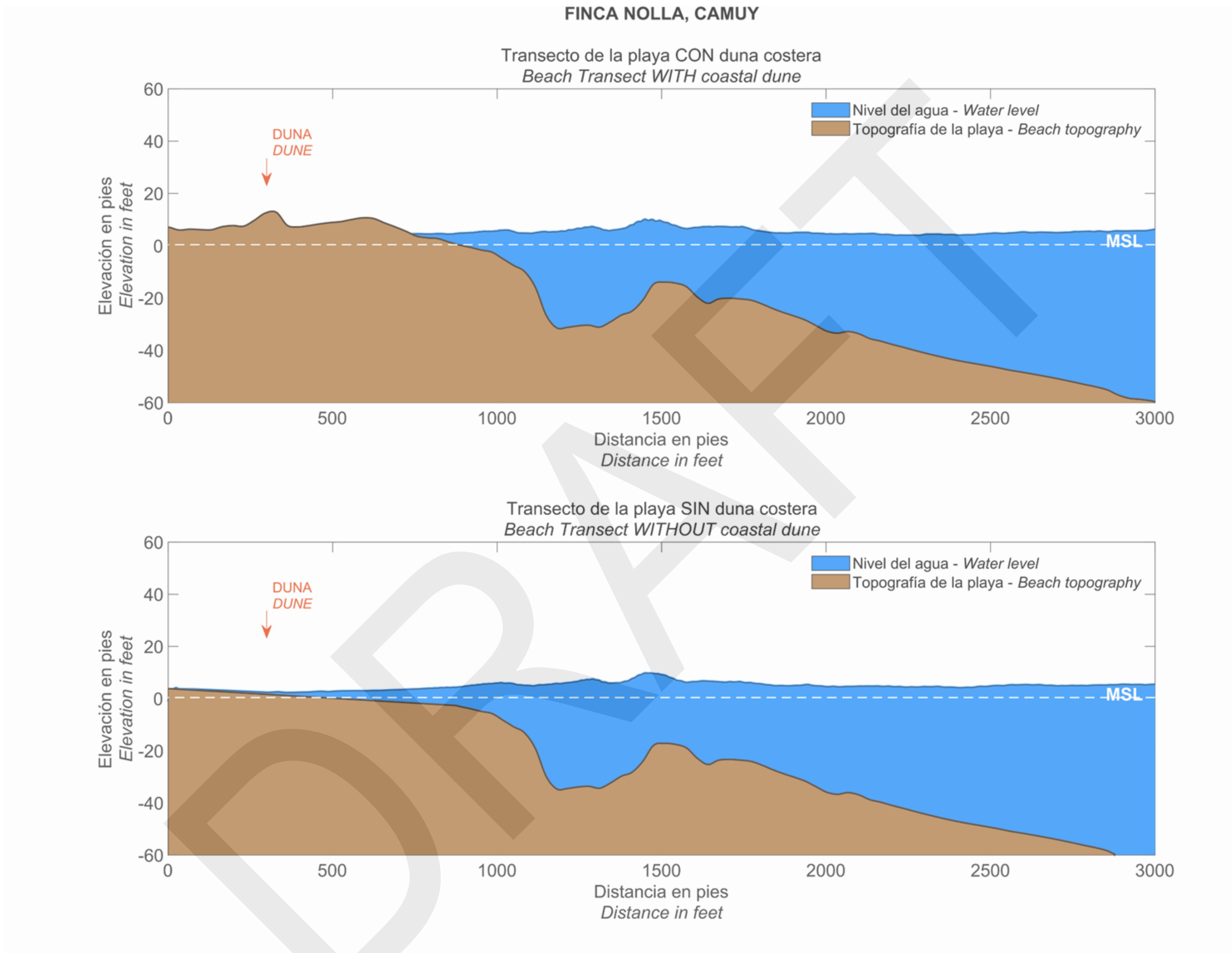


Fig. 16 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Finca Nolla, Camuy. Horizontal gray line denotes the mean sea level.

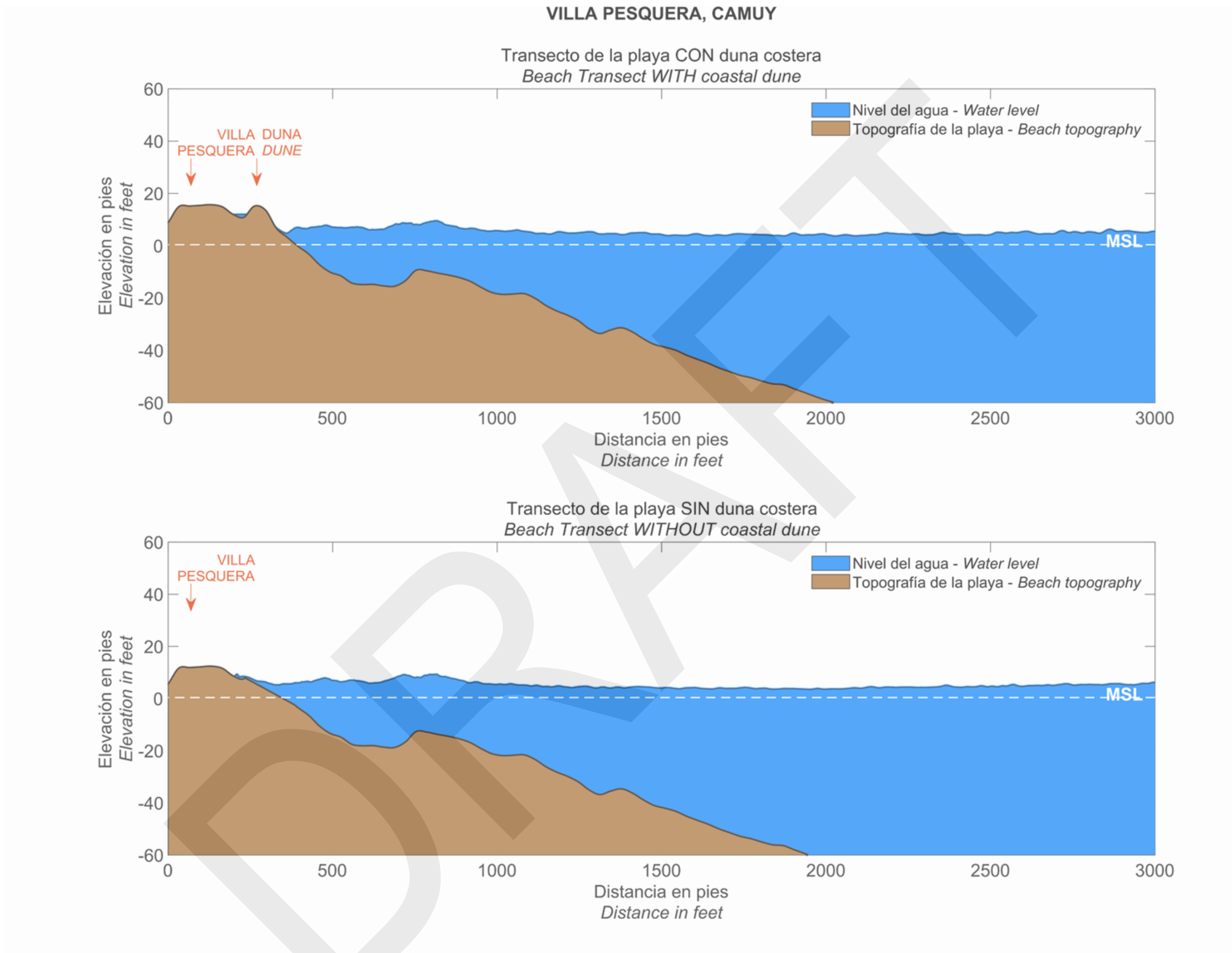


Fig. 17 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Villa Pesquera, Camuy. Horizontal gray line denotes the mean sea level.

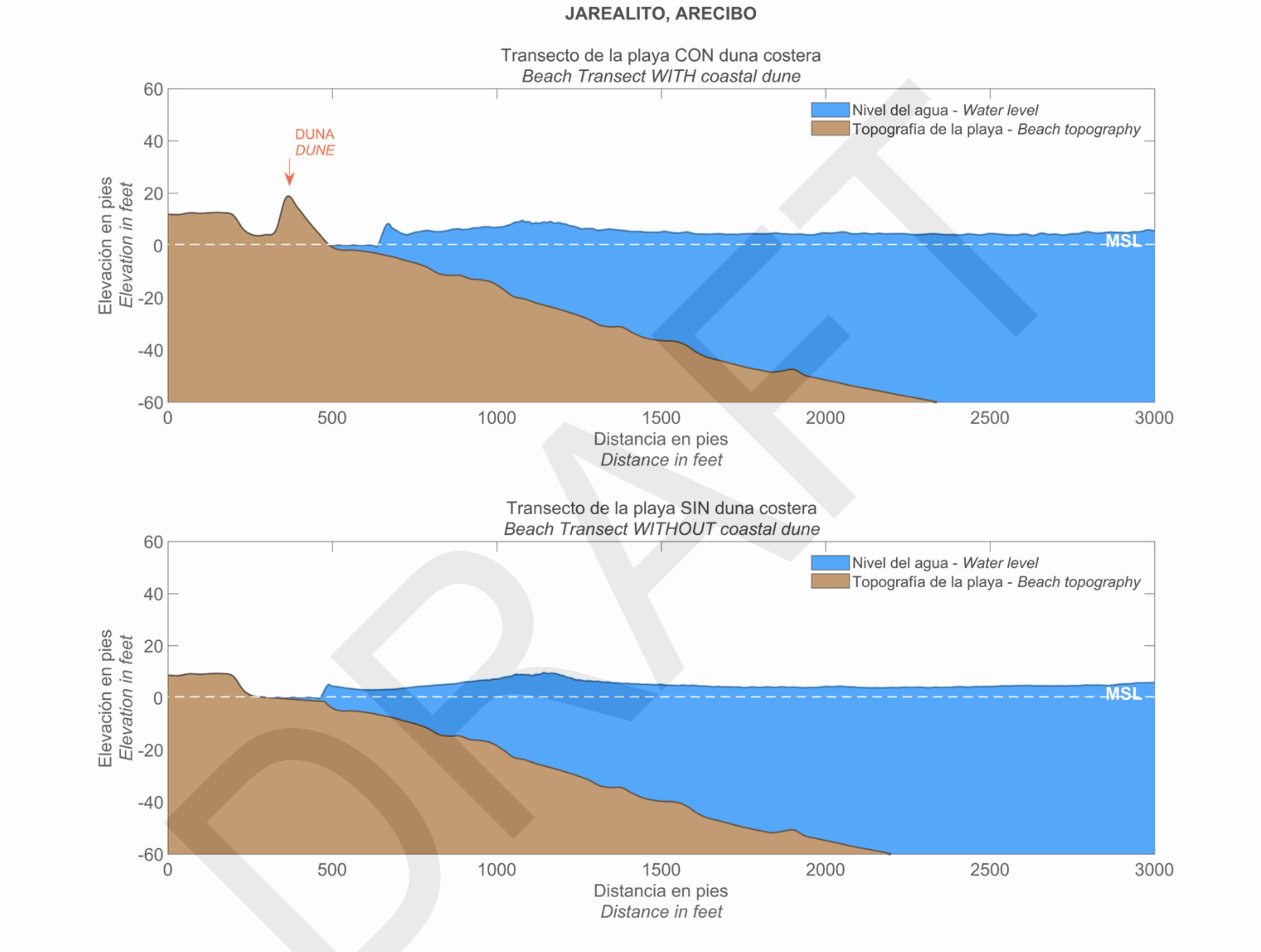




Fig. 18 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Jarealito, Arecibo. Horizontal gray line denotes the mean sea level.

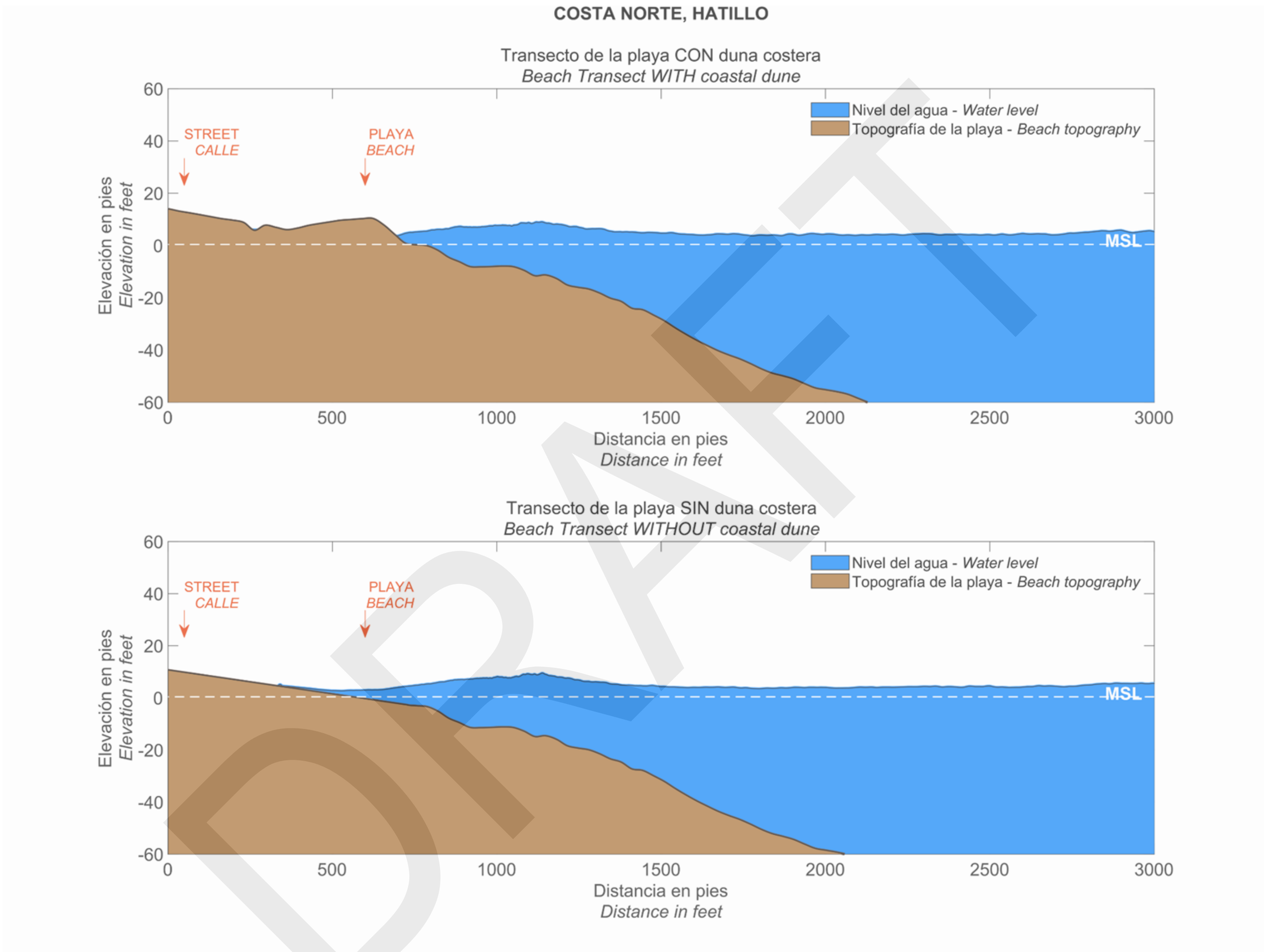



Fig. 19 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Costa Norte, Arecibo. Horizontal gray line denotes the mean sea level.

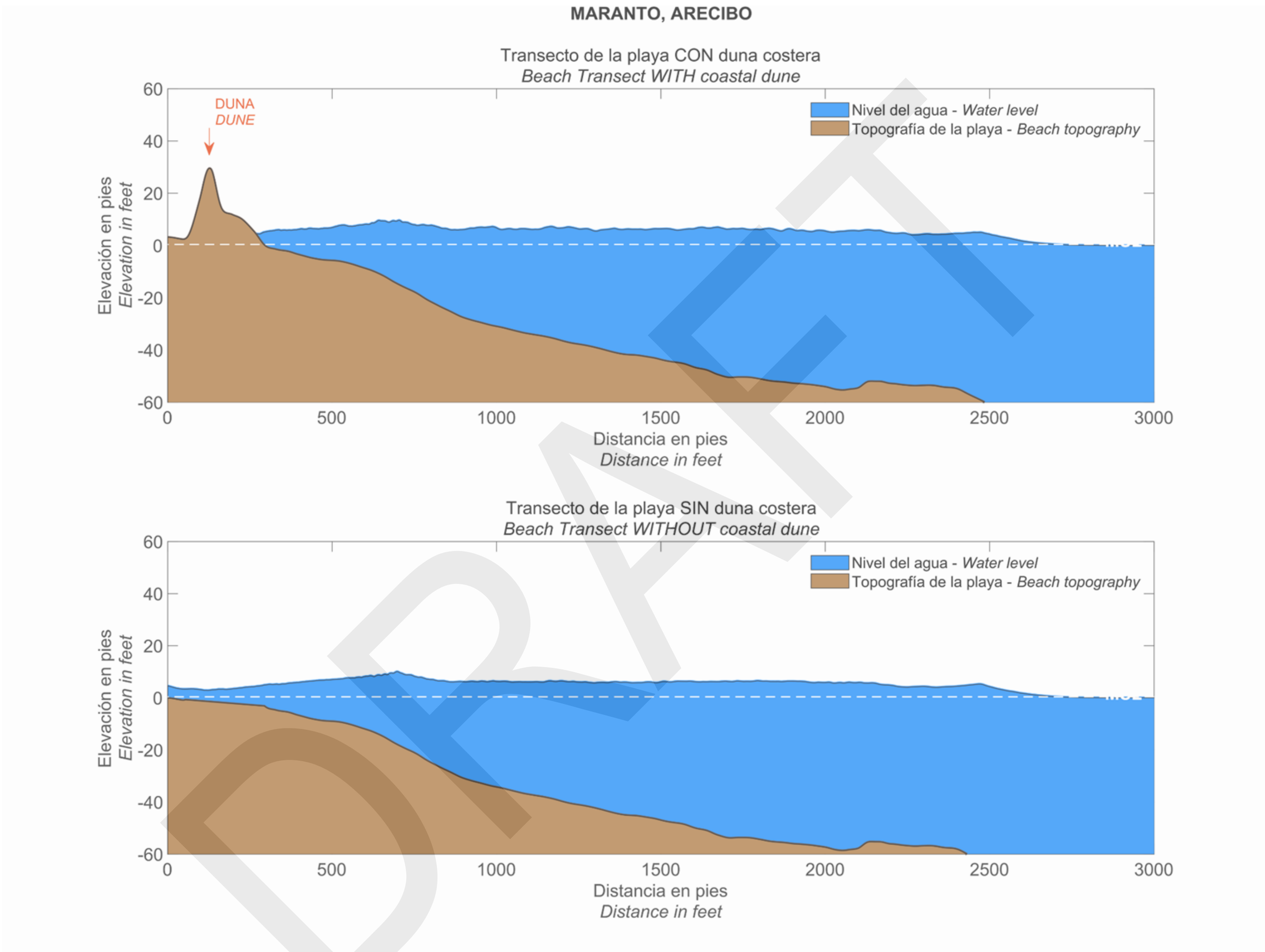


Fig. 20 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Maranto, Arecibo. Horizontal gray line denotes the mean sea level.

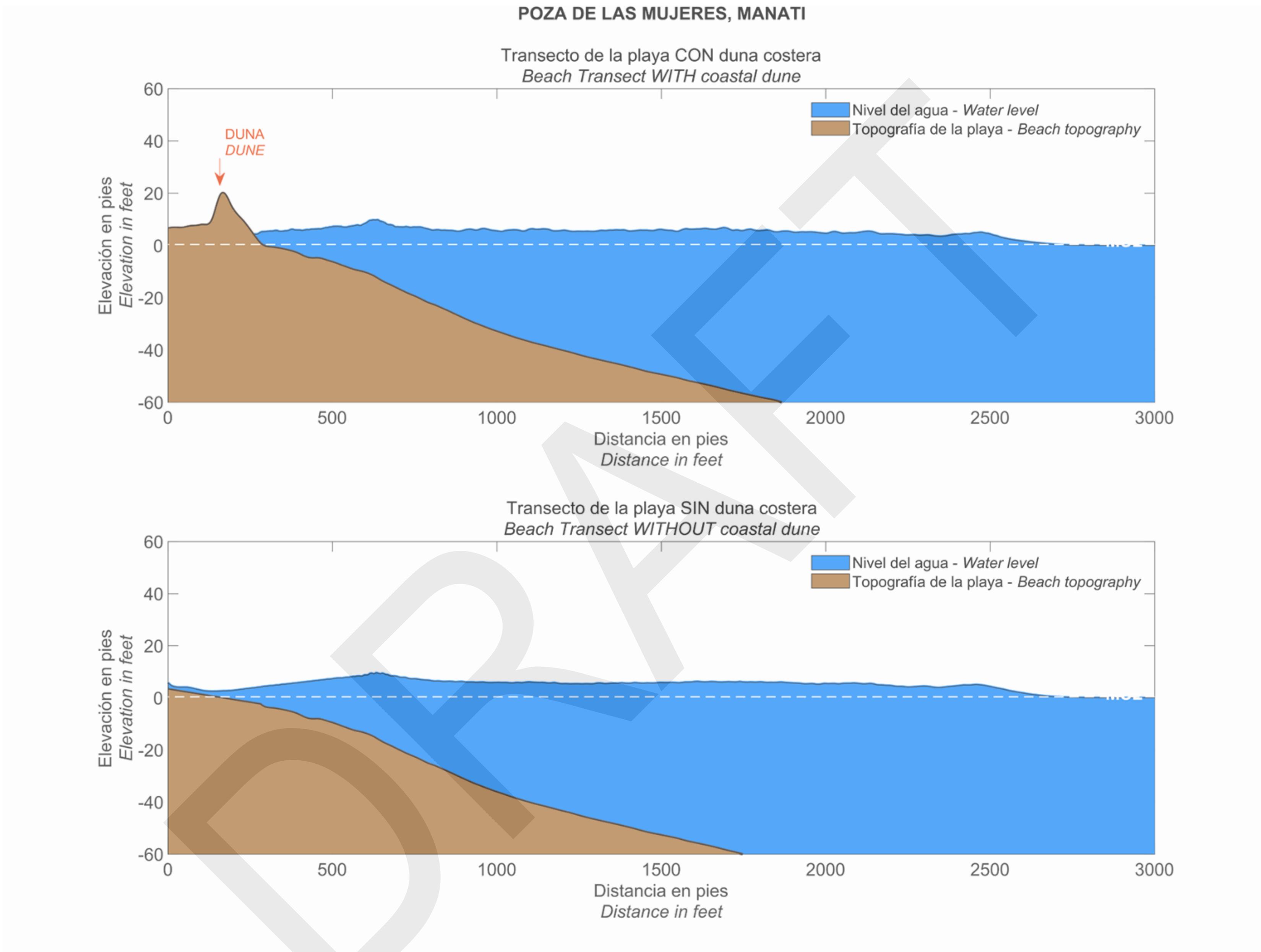


Fig. 21 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Poza de las Mujeres, Manatí. Horizontal gray line denotes the mean sea level.

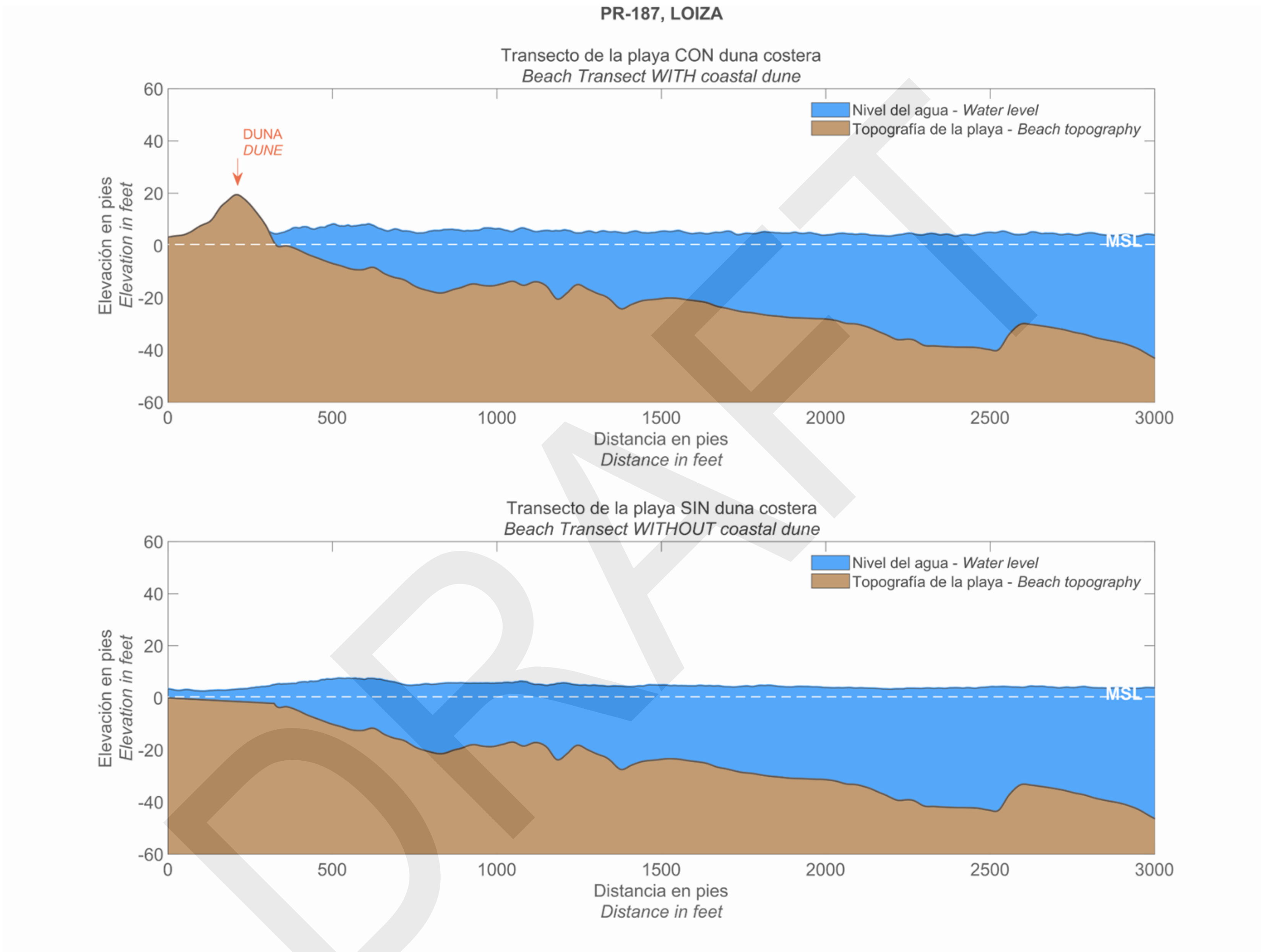


Fig. 22 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in PR-187, Loíza. Horizontal gray line denotes the mean sea level.

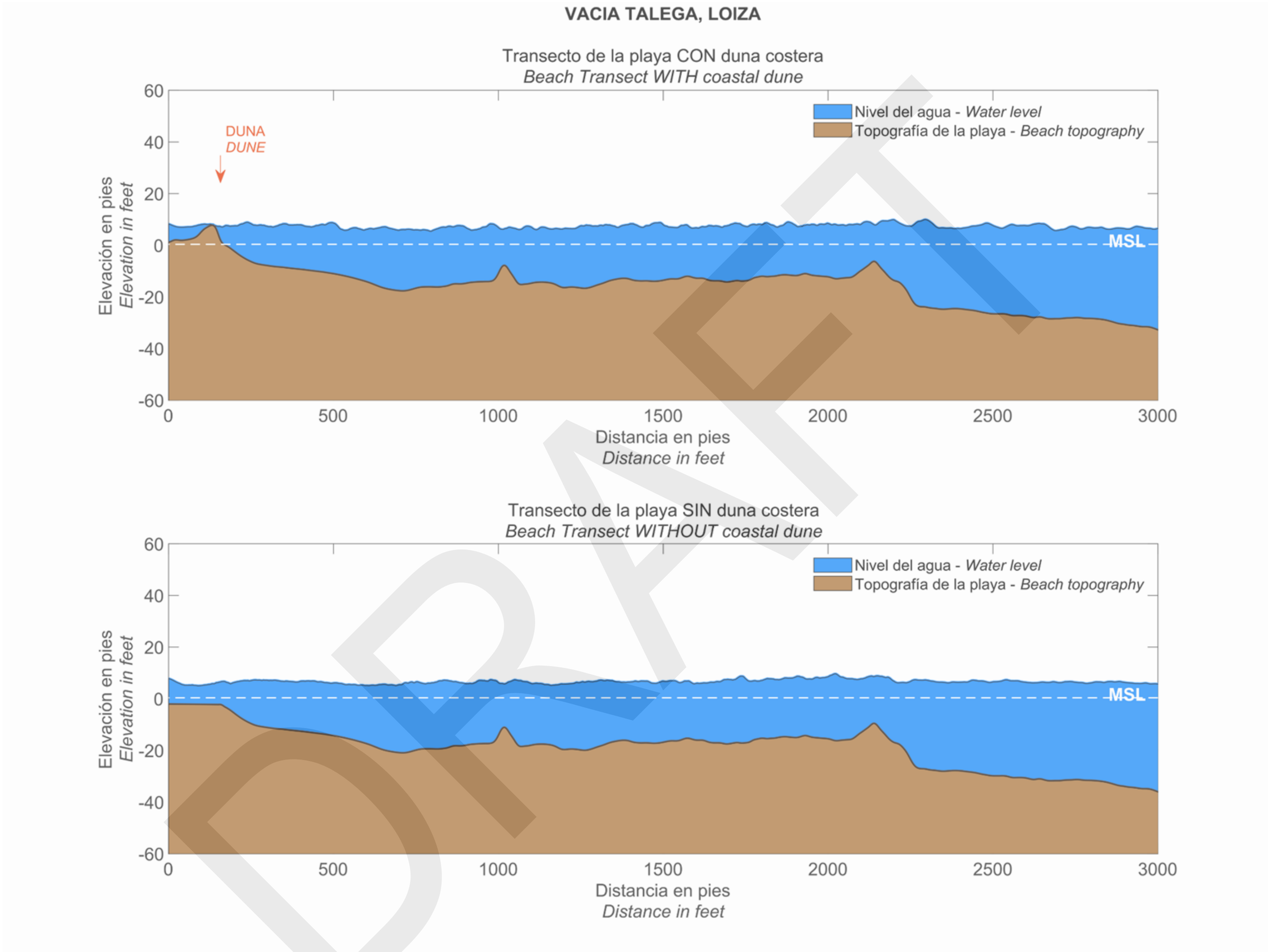




Fig. 23 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Vacía Talega, Loíza. Horizontal gray line denotes the mean sea level.

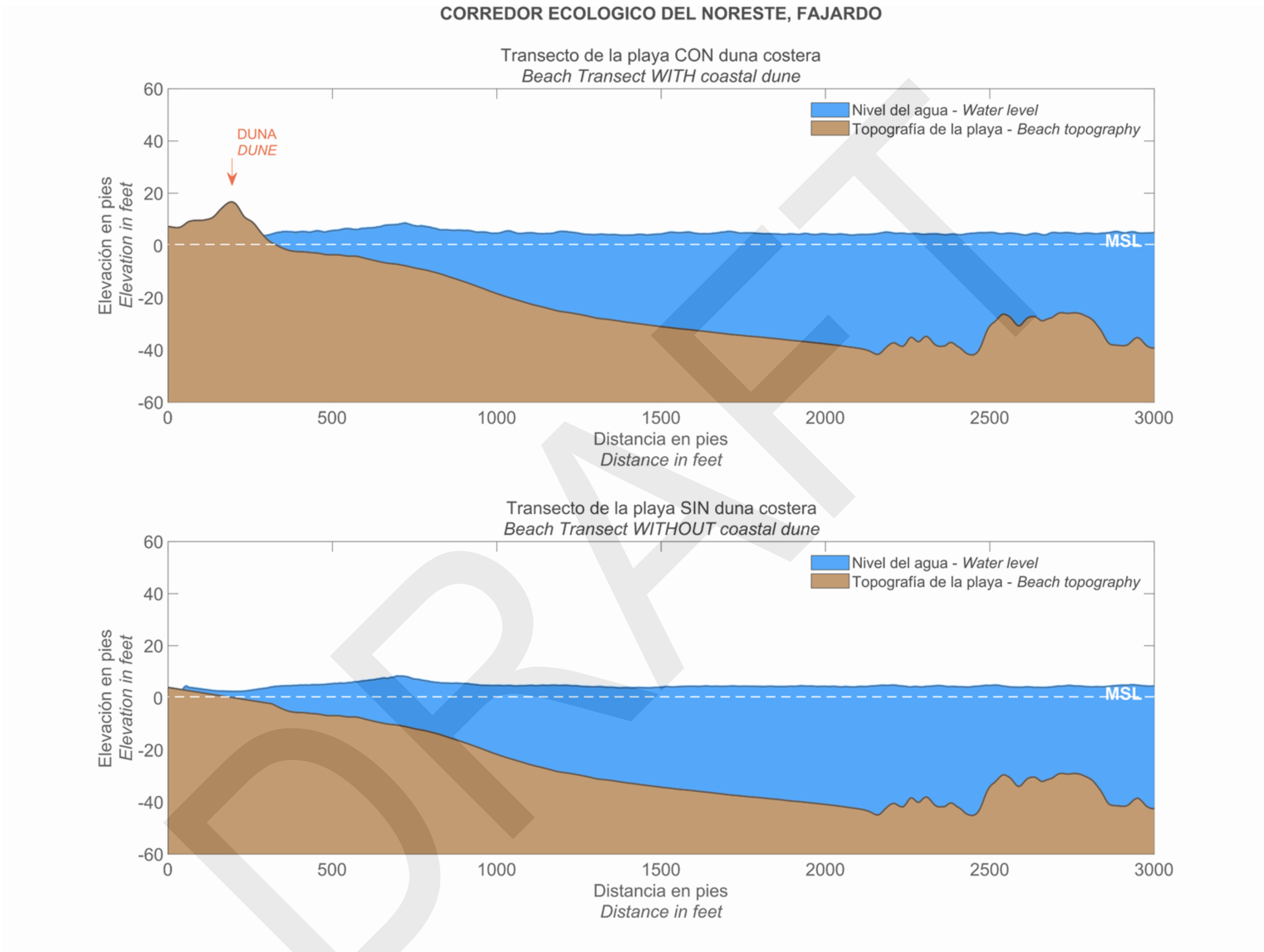


Fig. 24 Simulated (blue color) storm-induced flow on a beach profile (top panel) WITH (pre-storm conditions) and (bottom panel) WITHOUT (post-storm conditions) coastal sand dunes in Corredor Ecológico del Noreste, Fajardo. Horizontal gray line denotes the mean sea level.

## 5. SUMMARY

**It is important to recall that this initiative is only a simple analysis, more hypothetical than realistic, because a more detailed analysis needs to be performed to consider 2- and/or 3-dimensional physical features, local geomorphology, wind conditions, storm surge, storm-induced currents, and sediment transport, as well as other oceanographic parameters, to understand the dynamics controlling the local nearshore/coastal processes.** The numerical simulations confirmed that stabilized coastal dunes could protect nearby critical infrastructure and reduce damages from flooding and severe storm surge. The numerical simulations also indicated that the extent of the coastal/nearshore zones play an integral role in coastal hazard mitigation strategies and confirms that with larger volume of sediment and a wide beach, the coast will take longer to erode and will attenuate more wave energy.

The work presented demonstrates that can be replicated throughout the island. This project will lay the groundwork for a well-connected and robust system of dunes that buffer critical habitats, community resources, and cultural assets. Our strategies build off lessons learned post-extreme storms to demonstrate how strategic and intentional dune restoration activities and sediment trapping processes can re-establish a natural buffer for protecting critical habitats, as well as important social and infrastructure assets. This process allows the dunes to endure battering of the sea and even loss of dune front during storms, while protecting and promoting functionality of ecosystems behind them (Tong and Lin 2016). These approaches may also be relevant and applicable to other Caribbean islands that face similar risks to rising waters and storm surge.

Because the preservation and restoration of coastal sand dunes is a community responsibility, signages (Fig. 25) will be design and install to educate beach users about the importance of dunes and the restoration projects taking place at each site. The signage will include information about what is a coastal dune, their primary role, their conservation threats, and the adverse effect of its destruction (i.e, erosion, inland inundations, no area to attenuate storm wave energy, no area for turtle nesting).

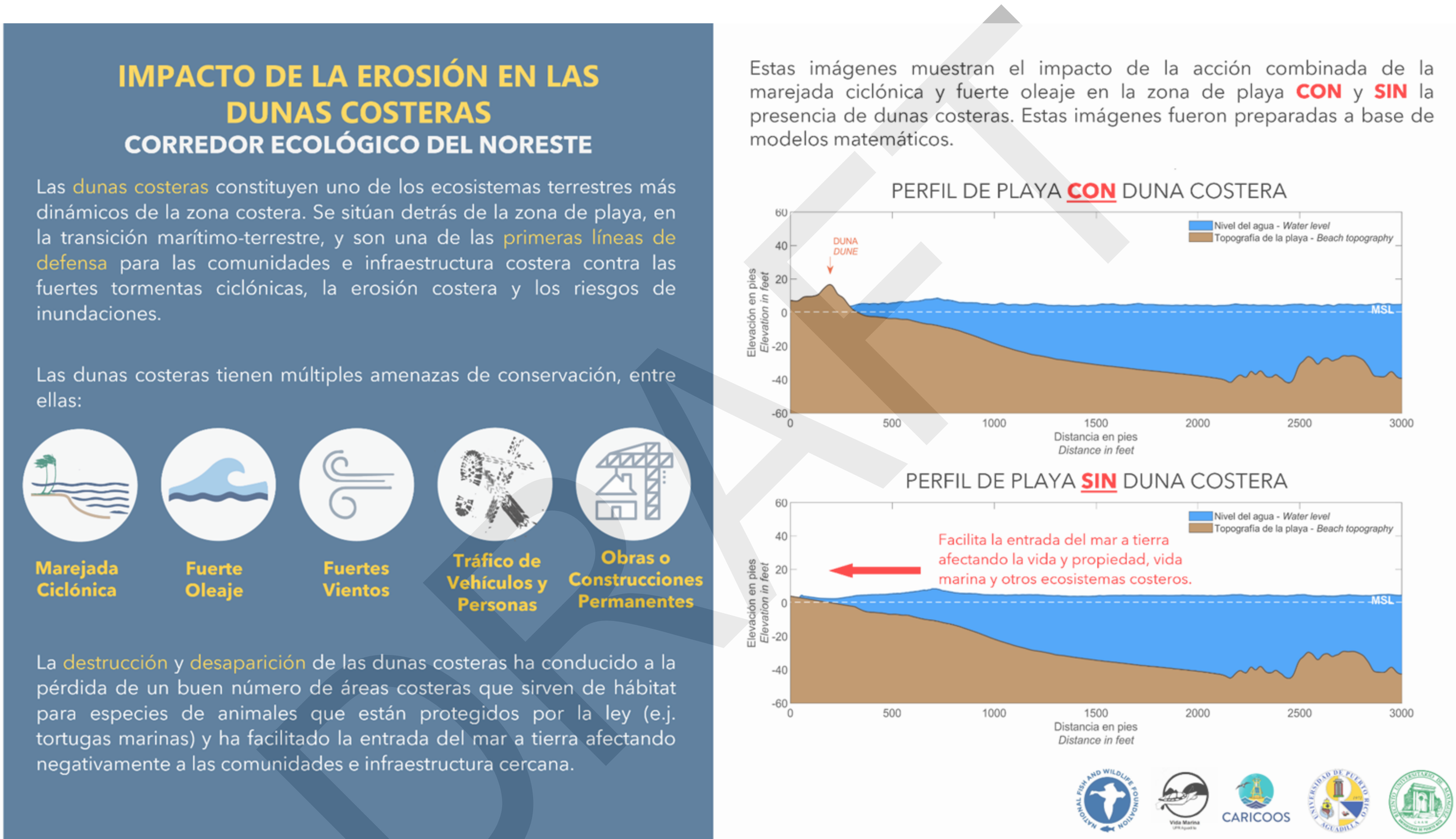


Fig. 25 Example of the signage designed to educate beach users about the importance of dunes and the restoration projects taking place at each site

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