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# IMPORTANCE OF REEFS AND DUNES IN THE PROTECTION OF THE COAST

TECHNICAL SERIES. The role of natural systems in coastal dynamics in the Mexican Caribbean and the impact of human activities in its current condition

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Rosalba Becerra

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# INTRODUCTION

**The Mexican Caribbean** has a great biodiversity and it is very important economically for Mexico for the great touristic industry developed there. However, it is a zone exposed to hurricanes and its beaches are subject to erosion processes.

Natural systems, such as seagrasses, coastal dunes and mangroves, are essential elements of coastal dynamics. The degradation of these systems has altered such dynamics causing beach erosion, more flooding derived from heavy rains and more damages from storms' surge.

In spite of its importance, the functioning of these systems is not well known by local inhabitants, decision makers and entrepreneurs, which has allowed the destruction of these valuable natural systems without recognizing the negative consequences that such degradation will have in coastal infraestructure and people.

The functioning of these natural systems has been studied by research centers as the Engineering Institute and the Institute of Marine Science of the UNAM, by the CINVESTAV and other Mexican and foreign universities, so there is a sound scientific support to prove its importance.

The objective of this report is to show the importance of natural systems as means for coastal protection, focusing in coral reefs and coastal dunes through the compilation of recent scientific information, the exposition of the results, the explanation of the methodology used and the compilation of a broad range of scientific references to support it.

Akumal Bay. Photo: Fernando Secaira/TNC.

# 1. THE BARRIER REEF PROTECTS THE COAST

## 1.1 The barrier reef and crests dissipate the energy of waves and storm surges reducing the impact on the coastal dunes and infrastructure

Reefs protection service is widely documented. Ferrario et al. (2014) compiled 255 scientific papers describing the reefs' role in wave attenuation. One of the clearest examples in a scenario of extreme conditions might be that of the Mexican Caribbean. Hurricane Wilma which was one of the most destructive hurricanes ever caused the greatest economic loss in Mexican history estimated to be of 30 billion pesos (Silva et al. 2012; Avelar 2006). It affected the coasts of Quintana Roo, from October 20 to 23, 2005. It made landfall on October the 22nd between Cancun and Puerto Morelos, then inched overland until reaching the South of the Gulf of Mexico after October 24. Two contrasting effects were noted, one marked erosion was observed in 12 km of beach in Cancun, sufficient that artificial restoring was deemed necessary; while in Puerto Morelos the beach width increased up to 30 m (Silva et al., 2006; Mariño-Tapia et al. 2014). The difference between the sites is that Cancun is an exposed system while the beaches of Puerto Morelos are protected by a reef (see Figure 1).

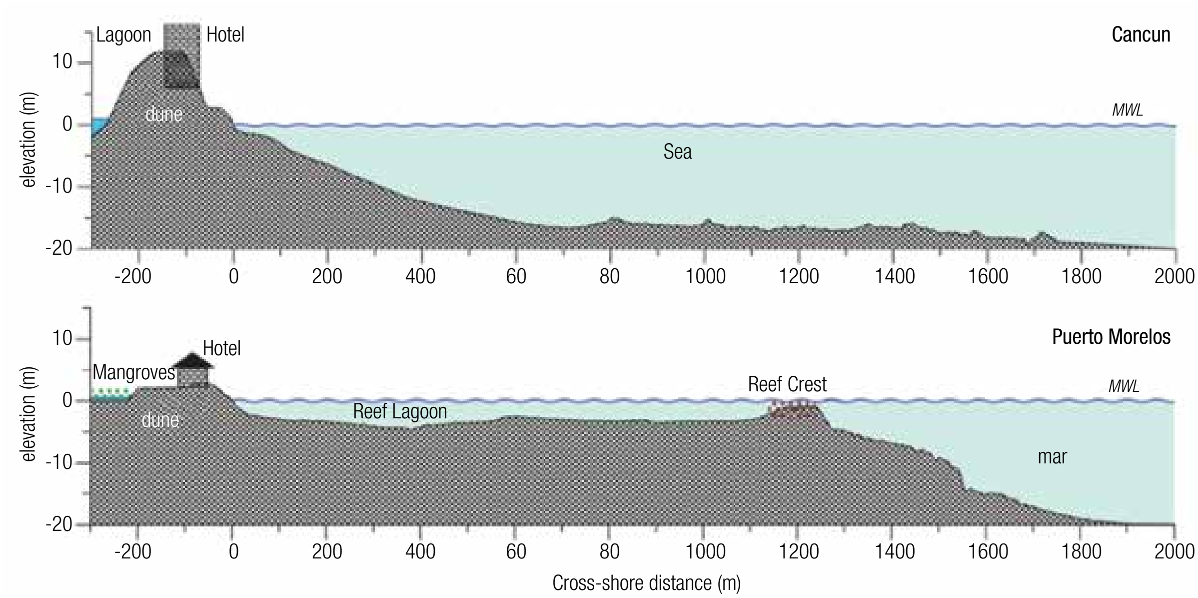


**Figure 1.** Schematic diagram of the profile perpendicular to the coast of the middle sections of Cancun and Puerto Morelos, from topographic measures and bathymetric data. The mean water level (MWL) is 0 m (taken from Alegria-Arzaburu, 2013).

### 1.1.1 Geomorphological differences

#### *Cancun*

Cancun is a barrier island system with an open beach, formed by biogenic carbonate sediments (average particle size, 0.4 mm), and limited by two rocky tops: Punta Cancun and Punta Nizuc (Figure 2). The Nichupte lagoon complex is formed by small bodies partially separated by rocky formations and mangrove swamps (Guido et al. 2009). It is important to emphasize that before tourism development, the beach was wider with a width of 100 to 400 m (Figure 3), and was protected by a dune of about 12 m in height above mean sea level (MSL). The lagoon had two permanent connections to the Caribbean: in the North, there was an opening West to Punta Cancun and in the South, there was an opening West to Punta Nizuc. It also had temporary openings in the front of the beach. These entrances facilitated water exchange and kept the hydrological balance between the lagoon and the sea (Silva et al. 2006).

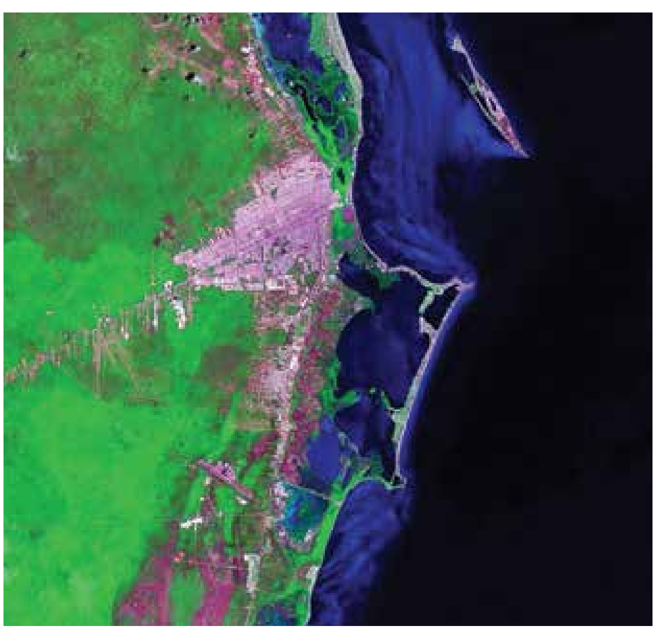

**Figure 2.** Satellite image from the city of Cancun, barrier island and lagoon (Bryant, 2015).

In 1970, development of hotel infrastructure began which modified the barrier island. One of the first changes was filling some areas so that the size of the island could reach between 250-300 m and large hotels and the golf course Pok Ta Pok could fit in.

The invasion of dunes and beaches by the construction of hotels continued over the following years (Rodríguez 2007). The evolution of the width of the beach in relation to the number of buildings present in the area is shown in Table 1. The vegetation layer over the bar that prevented sediment loss, disappeared completely after 1990.


**Figure 3.** Punta Cancun in 1967 y 2005 (taken from Silva et al. 2006).

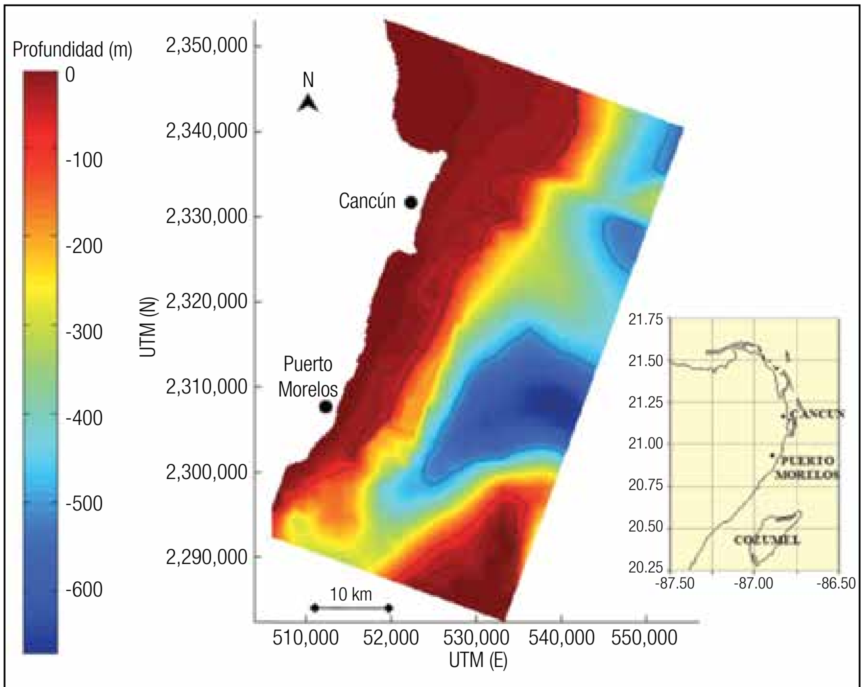


**Figure 4.** Bathymetric map of Cancun and Puerto Morelos (taken from Mariño-Tapia et al. 2014).

Table 1. **Wide beaches evolution and N° of buildings in Cancun (modified from Ramírez, 2007)**

| *Year* | *Wide dry beach* | | | *N° of buildings* | |
|---|---|---|---|---|---|
| | *Maximum* | *Medium* | *Minimum* | *Working* | *In construction* |
| 1970 | 106.89 | 70.95 | 24.80 | - | - |
| 1985 | 96.45 | 42.69 | 6.06 | 17 | 9 |
| 1990 | 44.98 | 17.40 | 0 | 54 | 3 |
| 1999 | 37.13 | 16.26 | 0 | 63 | 4 |
| 2013 | 50 | - | 25 | - | - |

### *Puerto Morelos*

As in Cancun, the beaches system is composed by carbonate sediments (particle size 0.2 mm); however, it is protected by a reef edge that extends for 4 km (Coronado et al. 2007). The beach is stable, with a width of 85 to 90 meters and the dune has been preserved at about 4 m above mean water level (Alegria-Arzaburu et al. 2013. The shallow reef lagoon (3 to 4 m of depth) is connected to the open sea by two entries in the North and a navigation channel in the South. The sediments are consolidated by sea-grasses and the reef zone is characterized by the presence of shallow coral banks exposed to wave action (Coronado et al. 2007).

## 1.1.2 Hydrodynamics

The tide in both areas is semi-diurnal and has a range between 0.32 and 0.07 m (average, 0.17 m). Most of the time (under normal conditions), waves approach from East/Southeast and near 90% of waves have significant height (Hs)[1] of 0.5 to 1.5 m, with a mean period (Tm) of 4 to 6 s. During Winter, North winds generate stronger waves with Hs of 6 to 15 m and last longer periods, Tm ~8 to 12 (Ruiz de Alegria-Arzaburu et al. 2013). From May to October hurricanes are common, which can generate waves with up to an Hs of 6 to 15 m and periods of 8 to 12 s (Mariño-Tapia et al. 2014).

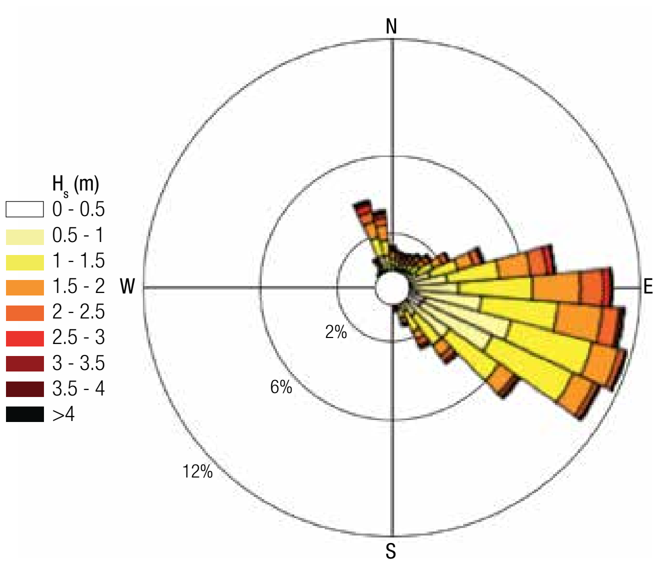


**Figure 5.** Wave rise, determinated with data of "buoy 42056" owned to NOAA, from September 2007 to May 2011 (taken from Ruiz de Alegria-Arzaburu et al. 2013).

## 1.1.3 Protection in storm conditions

Cancun and Puerto Morelos are located in one of the zones with more wave energy in the Gulf of Mexico and Caribbean due to exposure to tropical storms (Silva et al. 2012; Figure 6). Between 1948 and 2007 there have been 47 hurricanes, of which 7 have exceeded significant wave heights (Hs) of 10 m: Allen (1980), Gilberto (1988), Roxanne (1995), Isidoro (2002), Emily (2005) and Wilma (2005).

Hurricane Wilma was one of the most destructive and caused the greatest economic loss in Mexico. Also, it was one of the hurricanes with lowest pressure registered (822 mbar) and the fastest growth, with wind speeds increasing from 111.2 km/h to 277.8 km/h in 24 h (Pasch et al. 2014). Hurricane Wilma affected the coasts of Cancun between October 20 and 23, 2005. It made landfall on October 22, between Cancun and Puerto Morelos. Due to a high-pressure system North of Wilma, the hurricane stayed in the area and moved slowly to the South of the Gulf of Mexico, 24 hours later. The slow movement over the area increased the impact on the coast and amplified the severe erosion of the beaches in Cancun (Silva et al. 2012).

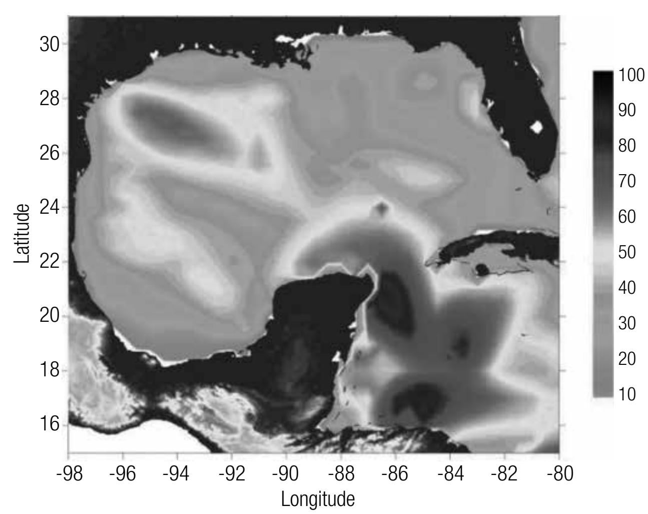


**Figure 6.** Energy map of the storms and hurricanes of the Gulf of Mexico and Caribbean. The energy level is represented by the color (normalize) made by extreme meteorological phenomena between 1958 and 2007 (taken from Silvia et al. 2012).

[1] Hs: Average of third largest wave of a wave record.

### *Observations and results of field campaigns*

The effects on the morphology of the beaches of Cancun were measured using two field work; the first was conducted in August 2005, after Hurricane Emily and the second, three days after Wilma (Silva et al. 2006). The erosion was widespread along the 12 km stretch of Cancun's beaches; however differential responses were observed in four areas according to the study of Silva et al. 2006 (Figure 7):

- Section 1, in the South, near Punta Nizuc, showed considerable accretion, between 10 and 15 m.
- Section 2 showed serious erosion. In April 2005 the beach had widths of 25-28 m; after Wilma the beach disappeared completely exposing the rocky layer and several buildings had structural damage (Figure 8).
- Section 3 was also eroded, but to a less extent than section 2 and 4. It is important to highlight that this area starts right at Playa Delfines, the only section of approximately 1 km which has a dune and no buildings or hotels. The erosion was close to 1 m in height next to the buildings but the beach width showed little change. This was the area that showed more stability.
- Section 4, in the North side, showed the strongest erosion, the beach disappeared and the rocky layer was exposed. This level of erosion continued for 3.5 km to the north and gradually decreased.

Regarding Puerto Morelos, measurements show that coral reefs dissipate 90% of the wave energy (Figure 9, Blanchon et al. 2010). Unfortunately, there are no beach profiles as in Cancun, so changes were assessed comparing in situ photographs and satellite images (QuickBird) before (April 2005) and after Wilma (October 2005), showing a uniform beach width accretion up to 30 m. Satellite images show that the dune was eroded in several sections, (despite having vegetation), which probably contributed to the beaches accretion (Figure 10, Mariño et al. 2014). The effects were unusual, therefore the phenomenon was modeled to clarify the movement ( Ruiz de Alegria-Arzaburu et al. 2013; Mariño-Tapia et al. 2014).

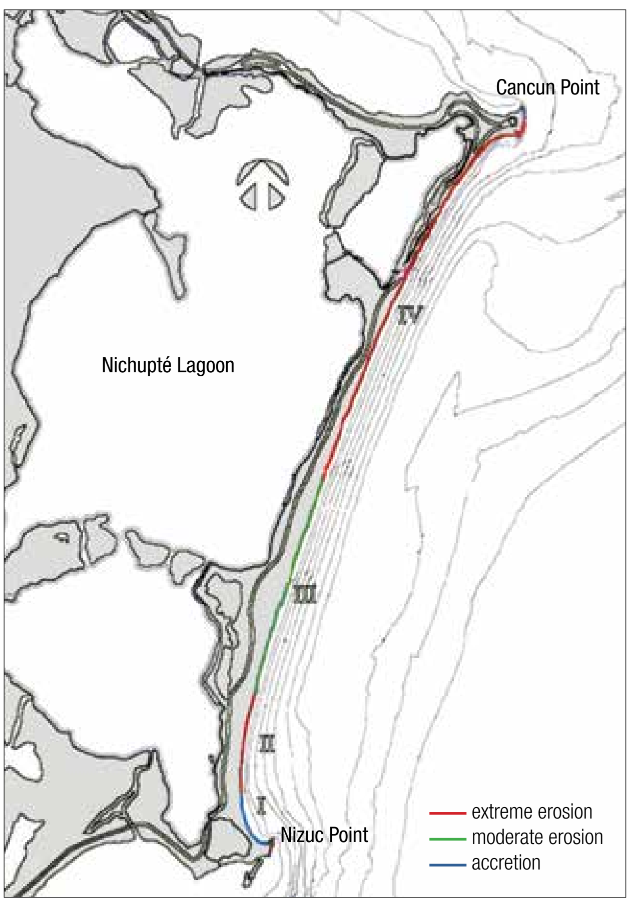


**Figure 7.** Areas in relation to the erosion caused by Hurricane Wilma.

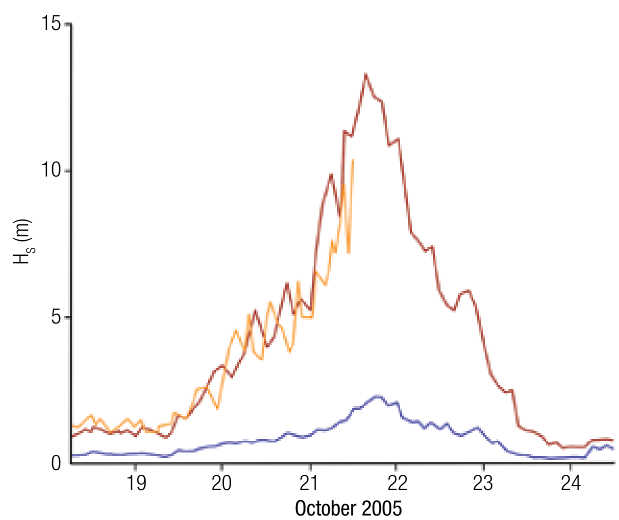


**Figure 9.** Significant wave height in Puerto Morelos and Cancun during Hurricane Wilma 2005. Red on the outside of the reef of Puerto Morelos (CICESE); yellow in Cancun (Rodolfo Silva) and, blue in the inside part of the lagoon of Puerto Morelos (Taken from Blanchon et al. 2010).


**Figure 8.** Section 2, before and after the Hurricane Wilma (Taken from Silva et al. 2006).


**Figure 10.** Hurricane Wilma effects. On top photos of Cancun and below photos of Puerto Morelos (taken from Mariño et al. 2014).

### *Modeling oceanographic dynamics caused by Hurricane Wilma in Cancun and Puerto Morelos coasts*

To understand these contrasting scenarios the model focused on three important moments of the storm: i) October 20, 00:00 hrs. when the storm surge approached the coast; ii) October 21, 18:00 hrs. when the peak of the waves occurred; iii) October 23, 12:00 hrs, when the hurricane eye made landfall and the coastal dynamics changed abruptly (Figure 11).

The model shows how hydrodynamics changed abruptly between the two regions due to the morphological differences (Figure 12, Figure 13 and Figure 14). Predictably, under these conditions, Cancun presented strong currents outward from the coast from the start of the storm surge until the hurricane landfall on October 23. This current usually dominates the hydrodynamics of these events in the shallow region, and transports large quantities of sand outside the system. Strong sand transport (South-East direction) for 50 hours caused severe beach erosion in Cancun (Mariño et al. 2014).

Conditions were different in Puerto Morelos. At the beginning of the storm surge, the incident swell was lower and the sand was transported to the coast, into the system. During its peak, on October 22, sand was transported South-East, outward of the system, in far less amounts compared to the transportation outside the reef lagoon. When the hurricane made landfall, the water level dropped rapidly allowing the reef to increase its ability to dissipate wave energy, which prevented the sand further leaving the system. These conditions probably induced sand deposition on the beach and with the contribution of the sand from the dune (see hypothesis of coastal dunes) caused the widening of the beaches of Puerto Morelos (Mariño et al. 2014).

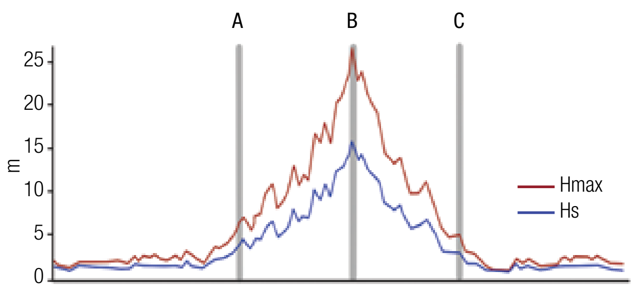


**Figure 11.** Maximum wave height (Hmax) and significant (Hs), measured during Hurricane Wilma with AWAC current profiler (Nortek) installed 20 m deep off the reef crest of Puerto Morelos (taken from Mariño et al. 2014).

**Mariño et al. 2014 Methodology**

The numerical model used to analyze the hydrodynamics and sediment transport caused by Hurricane Wilma was the 3D DELF. An area of 50 x 30 km (Figure 4) was used; with a 152 x 249 points grid; minimum resolution of 125m; 10 vertical levels with sigma coordinates and time step of 0.2 min. The wave propagation used data measured with an acoustic profiler (Nortek) installed 20m depths in front of Puerto Morelos and was implemented by the SWAN model. Wave, flow and hydrodynamic models are coupled. The wave model calculates the coefficient of stress radiation, which is introduced into the flow model in order to calculate currents; the hydrodynamic model evaluates the height of the water column, implemented for refraction of the currents that affects wave propagation (Mariño et al. 2014).

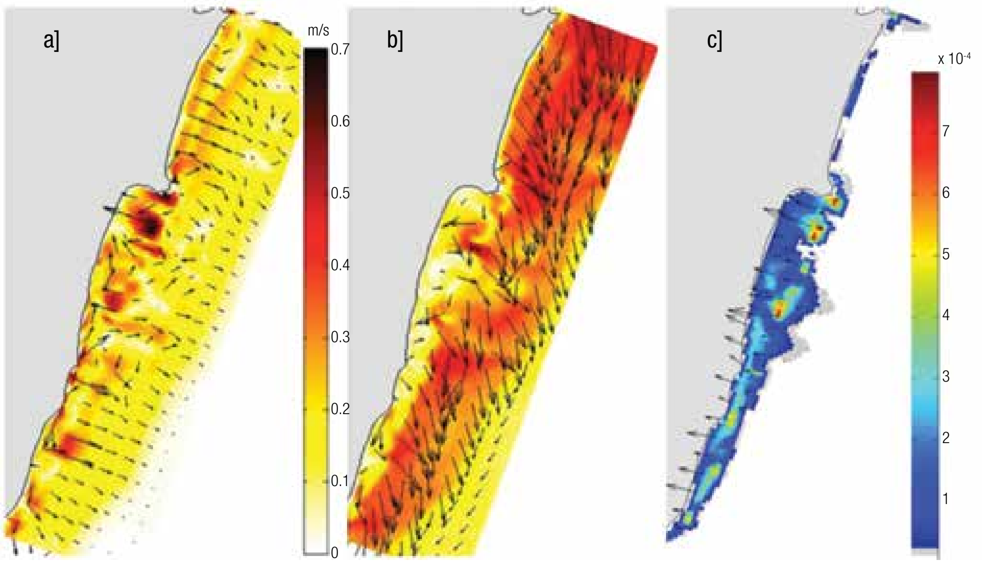


**Figure 12.** Model for October 20, 00:00 hrs. a] Swell + forcings by surface elevation; b] swell + wind + forcing by surface elevation; c] Sediment transport, wind scenario $m^3/m/s$ (taken from Mariño et al. 2014).

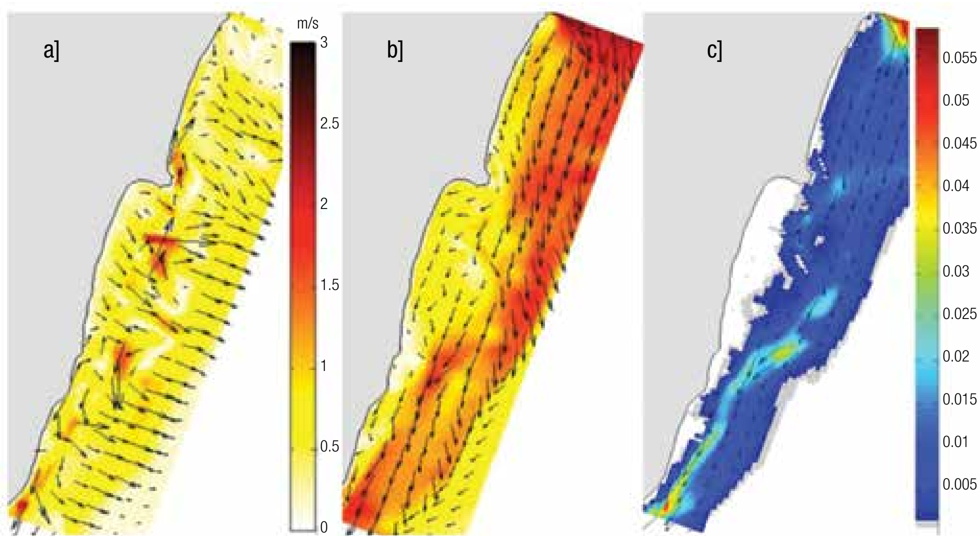


**Figure 13.** Model for October 22, 18:00 hrs. a] Swell + reinforcement by surface elevation; b] swell + wind + reinforcement by surface elevation; c] Sediment transport, wind scenario $m^3$ / m/s (taken from Mariño et al. 2014).

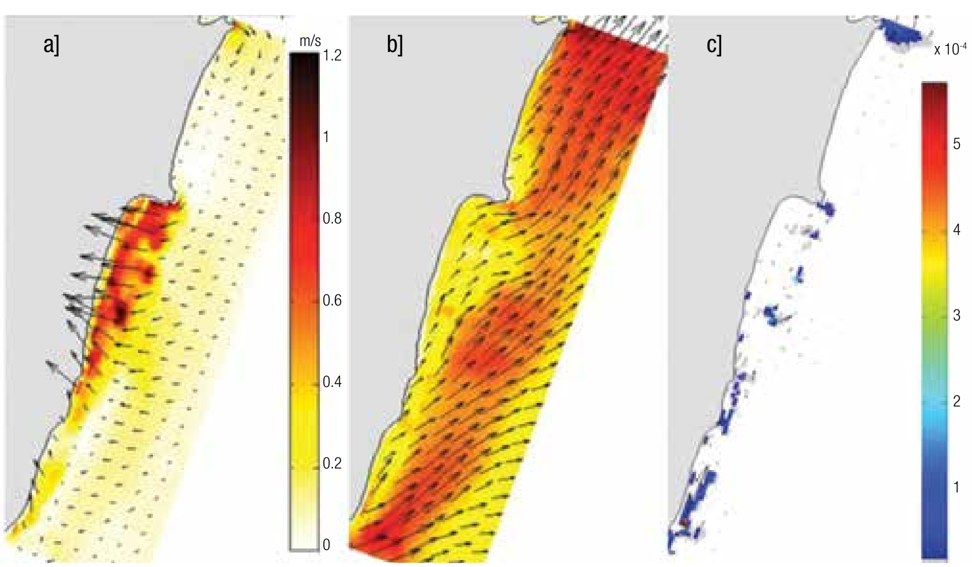


**Figure 14.** Figure 14: Model for October 23, 12:00 hrs. a] Swell + reinforcement by surface elevation; b] swell + wind + reinforcement by surface elevation; c] Sediment transport, wind scenario $m^3$ / m/s (taken from Mariño et al. 2014).

### 1.1.4 Protection under standard or typical conditions

#### *Field campaign results (Ruiz de Alegria-Arzaburu et al. 2013)*

The reef provides protection not only in storm conditions but also in calm conditions, that is, with the typical swell in the area. For corroboration beach profiles were analyzed every 3 to 4 months between September 2007 and June 2009, in Cancun and Puerto Morelos; (see Figure 16, Ruiz de Alegria-Arzaburu et al. 2013). The results showed that the beach protected by the reef edge in Puerto Morelos is less dynamic than the exposed beach in Cancun. For the same wave conditions, Puerto Morelos showed changes of less that 0.5 m in heigth in most of its beaches; meanwhile beaches in Cancun showed changes up to 2 m (Ruiz de Alegria-Arzaburu et al. 2013); therefore Cancun has areas with 4 times more sand transport than Puerto Morelos.

#### *Modeling (Alegria-Arzaburu et al. 2013)*

The SWAN wave model was used to determine the dynamics of the two areas. The model was calibrated with measuring instruments anchored in and out of the lagoon of Puerto Morelos. It was found that the reef of Puerto Morelos can dissipate 65 to 40% of the wave energy (Hs=3m, T=7s) coming from the Northeast and East respectively; while the morphology of Cancun dissipates only between 25 and 15%. Therefore, the reef has the ability to reduce swell energy by 40 to 35% providing greater protection.

Another scenario that was tested was the coral degradation in which three cases were simulated: i] a reef over 1 m high; ii) a degraded reef, with less than 1 m height, and iii) less than 2 m high. In the case i, 10% of the energy of waves was reduced, similar to the current conditions of the reef. In cases ii and iii an increase of the wave energy with 10% and 20% was respectively obtained.

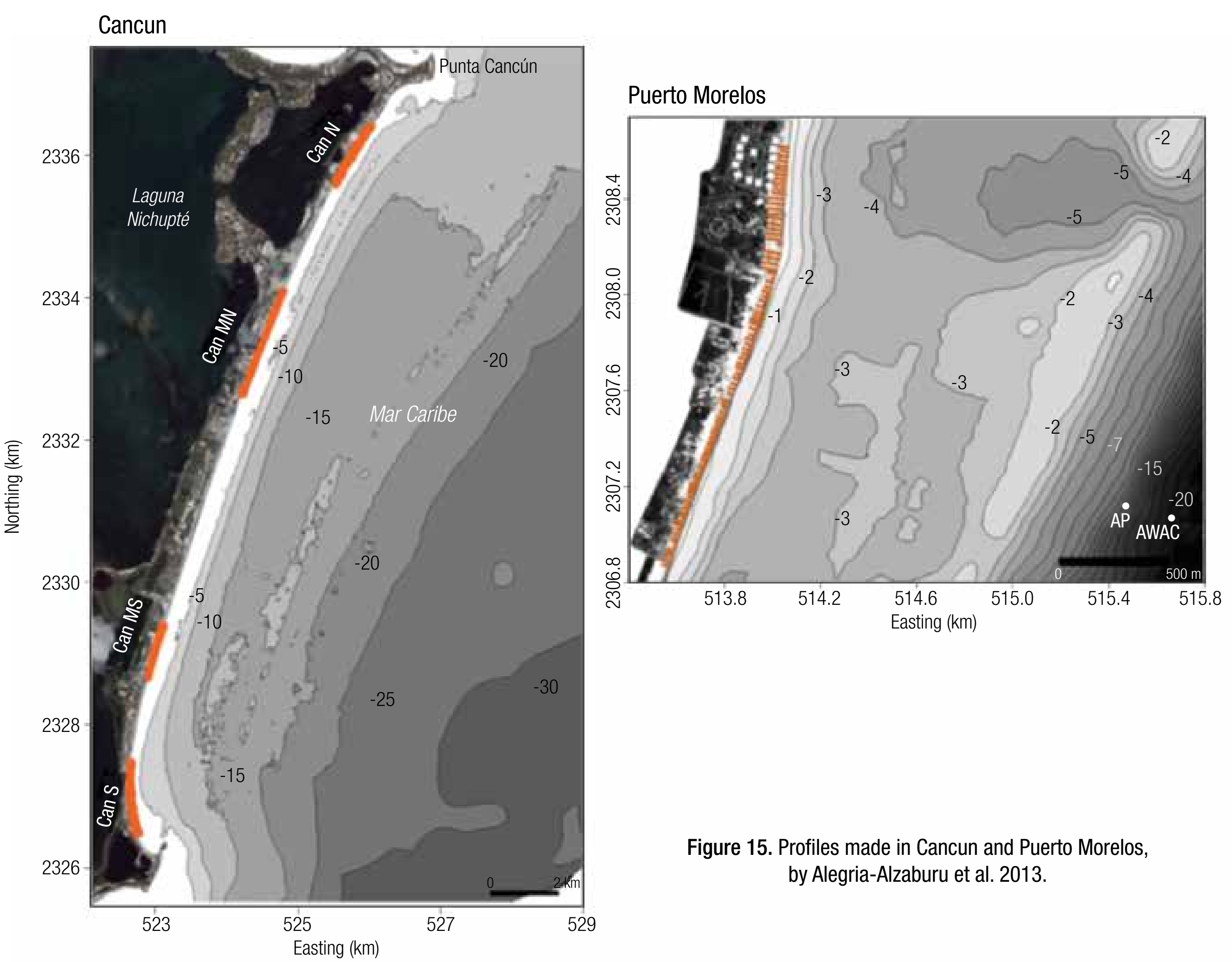


**Figure 15.** Profiles made in Cancun and Puerto Morelos, by Alegria-Alzaburu et al. 2013.

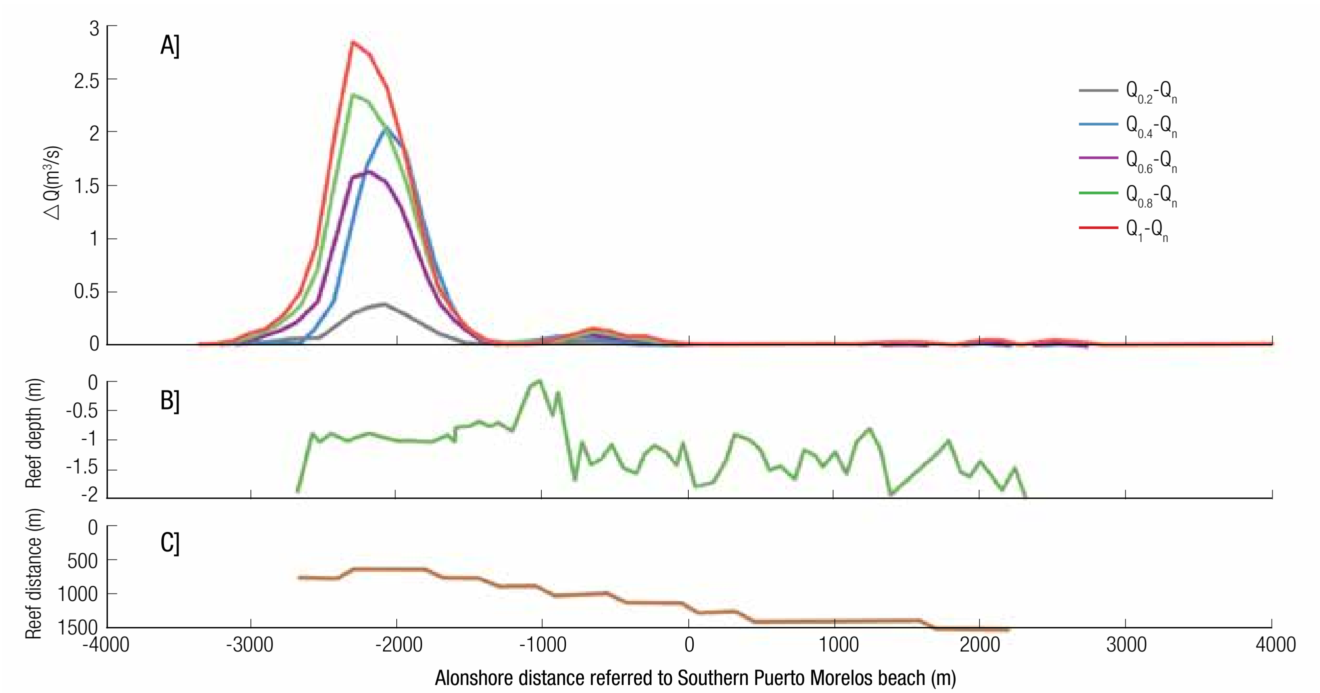


**Figure 16.** A] Difference between the actual sediment transport and the hypothetical case of sediment transport of reef crest with 0.2 to 1 m, B] actual reef high, C] distance between barrier reef and cost. The axis x, relates to the barrier reef length (4.5 km) studies were made between 0 to 2000 m, see figure 16 (taken from Alegria-Alzaburu et al. 2013).

It was found that sediment transport, obtained from the SWAN model values (height and swell direction) and depths, responds directly to reef degradation. The more degraded the reef crest, the greater the sediment transport, Figure 15 (Ruiz de Alegria-Arzaburu et al., 2013). This effect seems to be much more evident when the barrier reef is closer to the coast, which highlights its importance in sediment dynamics.

## Conclusion

The contrast between changes caused by Wilma in Puerto Morelos beaches and the beaches of Cancun is outstanding. The modeling made possible to reproduce sediment transport during the storm explaining how the barrier reef reduced the effect of waves and at times totally changed the dynamics, leading to the sand accumulation in Puerto Morelos. In contrast, the hurricane caused a current that carried the sand outside the system of Cancun for about 50 hours causing eroding beaches.

Scientists analized the differences under typical conditions. It was found that the reef of Puerto Morelos dissipates between 30 to 45% more wave energy than a beach without reefs, reducing sediment transport and consequently the beach is more stable. Finally, it was confirmed that a loss of 1 meter in the height of the barrier reef reduces wave dissipation capacity by 10%. This causes an increase in sediment transport and increases the erosion on the beach.

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### Ruiz de Alegria-Alzaburu et al. 2013 Methodology

The field work consisted of perpendicular profiles to the coast, spaced 20 m from the limit of the buildings until 0.5 m deep offshore measured in four areas of the beaches of Cancun and along Puerto Morelos (Figure 16) every 3 or 4 months between September 2007 and May 2011. The profiles were processed to calculate digital elevation models in three dimensions. Also, bathymetric data was acquired using an echo sounder (double-frequency SyQuest Bathy DF 500) coupled to a differential GPS, through perpendicular routes about 2 km, spaced between 100 to 400 meters, to depths between 1 and 20 m, with data limitations over the crest and in the surf zone filled out with interpolations. These data was complemented with databases of ETOPO-1 (NOAA-NGDC) and analyzed using empirical orthogonal functions with the objective of dividing the data into eigen-function space associated with a temporal coefficient (Ruiz de Alegria-Alzaburu et al. 2013), similar to what was done in a main component analysis.

The hydrodynamic model used wave and wind data provided by the buoy 42056-NOAA located 4,684 m deep. Three other instruments were also used: 1] an AWAC (Acoustic profiler of wave and current) installed from May to September 2007 to 2 km offshore from Puerto Morelos down to 20 m deep and, 2] an Aquadrop from July to September 2011 inside the lagoon down to 3 m deep and 3] an Aquadrop in the same period in the outside of the barrier reef down to 15 m deep. The data collected were used to implement the the wave propagation model; tide model was provided by CICESE. Wave modeling was carried out using SWAN model (Simulating Waves in Near-shore) in a domain with depths up to 675 m and resolution of 125 m. The wind was not taken into account and a uniform roughness was used (Roughness length, Kw = 0.1) along the entire domain. The objective of the model was to study the system response to structural changes of the reef. The mobility of the sediment was used to evaluate the degree of protection of the reef, following the energy approach of Bagnole, 1963 (Ruiz de Ruiz de Alegria-Arzaburu et al. 2013).


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## 1.2 **The probability that the sediment of the beaches will be transported out of the system is reduced by the barrier reef, allowing natural beach recovery possible**

As we have seen sediment transport is less dynamic in a protected beach as Puerto Morelos than in a exposed beach as Cancun. (Ruiz de Alegria-Arzaburu et al. 2013). This means that the reef helps keep sediment in the system, or at least they are transported at a slower rate. Two of the mechanisms that determine sediment transport are the parallel current to the coast and littoral drift (Figure 17).

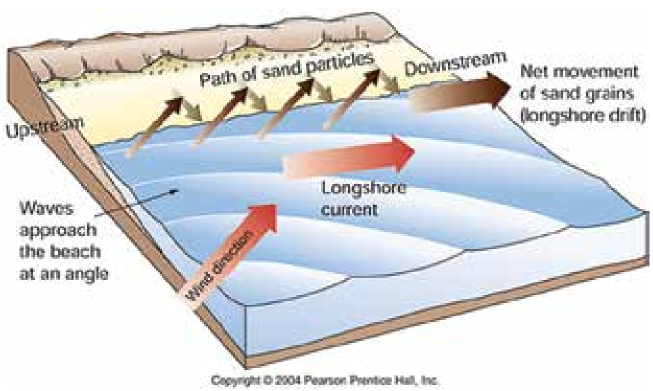


**Figure 17.** Diagram of the parallel current to the coast and littoral drift.

The waves usually have an impact on certain angle on the waterfront and as they approach the beach, interacting with the bottom in the same way. When the waves break, tension or stress is generated (radiation tensor) acting on the water itself, pushing it in a direction parallel to the coast known as longshore current, defined by the angle of incidence. (NOAA 2015). Depending on certain conditions, this current is responsible of the sediment transport (Goda 2000). Incident groups of waves do not break into a particular point, but along a zone. Therefore, the current parallel to the coast has a velocity gradient based on the depth and angle of incidence, see Figure 18 (Goda 2000).

Littoral drift is generated in a similar way. When the waves approach the beach with certain angle, they create a “zig zag” movement along the coastaline. (Figure 17). This movement carries the sediment up and down but the angle of incidence generates a net transport in parallel direction to the coast (NOAA 2015).

The transport mechanism is influenced by the energy of the incident wave: the higher the waves, the higher the transport, considering a fixed angle and slope (NOAA 2015). These two currents, the parallel and the drift, are able to modify the coastline. For example, in the case of Puerto Morelos (Figure 19) it has been observed that the most pronounced recesses (sections 1, 3, 5, 7, 11 and 12) match to coastal areas located off the mouths (Escudero 2011). The mouths are the places where the waves conserve more energy and therefore is expected to generate or produce higher sediment transport. Profile 7 is located in a section of the lagoon that is deeper than the rest allowing the stronger waves. On the other hand, profiles 2,

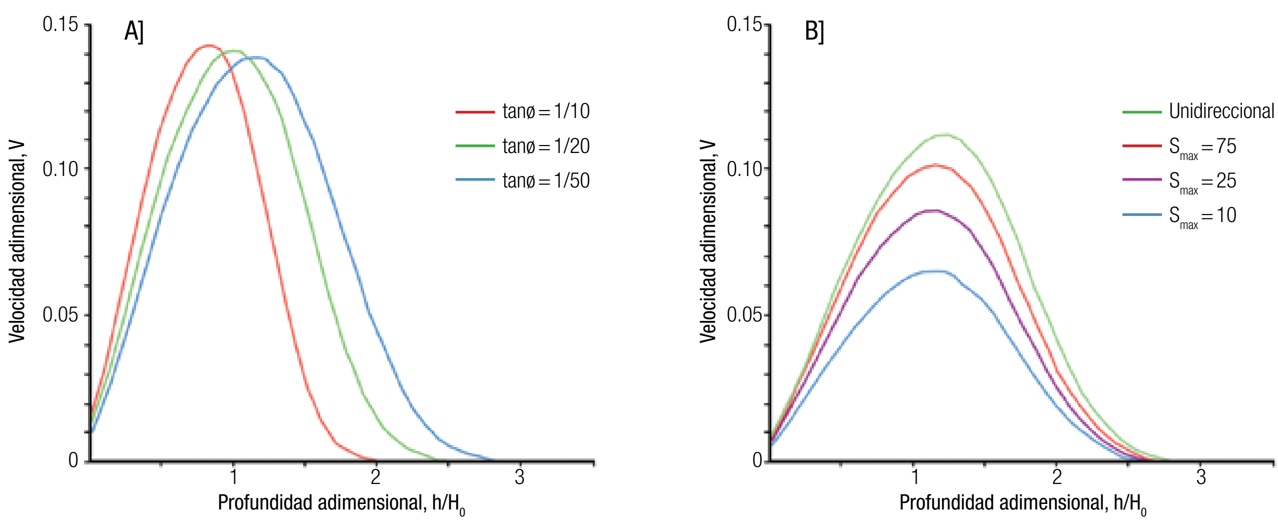


**Figure 18.** Current speed parallel to the coast with depth, with a model of random break. A] Depending on the slope, with fixed angle; B] according to the dispersion parameter, smax (given by the result of the frequency spectrum of Bretshneider-Mitsuyasu and the directional dispersion function of Mitsuyasu), with fixed slope [ 1/50 ] (taken from Goda 2000)..

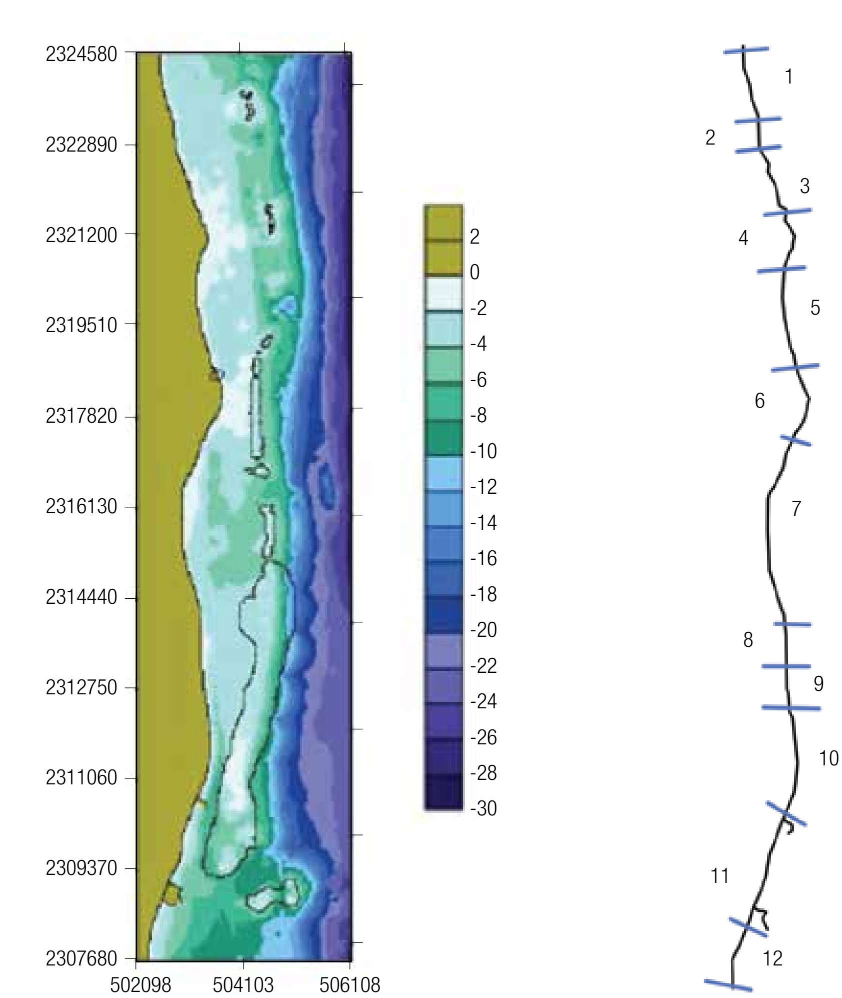


Figure 19. Left, detail bathymetry of Puerto Morelos; right, division by sections of the coastal line of Puerto Morelos (taken from Escudero 2011).

4, 6, 8 and 9 are protected by the barrier reef and the lagoon is shallow which increases friction of the bottom; therefore the incident wave energy is smaller and the sediment tends to be trapped forming projections (Escudero 2011).

## Conclusion

As we have seen the incident angle is important and the crest can change it. When waves break on the reef crest, these tend to be oriented perpendicularly to the coast. A wave with this direction has a limited capacity to transport sediments (Goda 2000, Mariño personal communication, 2016). Therefore, this also helps prevent coastal erosion.

The sediment transport depends on the strength and angle of the incident waves, both are modified by the barrier reef. Generally, the wave is attenuated and reoriented in perpendicular way to the coast, reducing sediment transport.

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## 1.3 **The barrier reef could increase the flood level due to the phenomenon of resonance**

Geomorphology is an important factor for determining risk of flooding, due to the interaction phenomena, it may exacerbate or dissipate the swell. The surf beat is an oscillation of the sea surface within the subtidal zone, related to the interaction of groups of incident waves (Nakaza and Hino, 1990), it may be affected by the phenomenon of resonance and the energy of the wave rupture (Roeber and Bricker 2015; Nakaza and Hino 1990).

Resonance, in a very general case, can be understood from the standing waves which are generated when a wave encounters an obstacle and it is reflected and the original wave span is amplified (Figure 20). The tsunami in 2009 in American Samoa provides a clear example of the effect and consequences of resonance in the areas adjacent to the coastal zone.

In the case of Samoa, thanks to a validated numerical model with in situ measurements (NEOWAVE), standing waves with periods of 3 to 18 seconds were identified, over the reef but also on the slope and platform of the islands (Roeber et al. 2010). These standing waves generated resonance at different scales on the bathymetry of the area. The consequences were obvious: those areas and cities not affected by resonance suffered less flooding even when its location would have expected a more severe effect (see Figure 21) (Roeber et al. 2010). It's important that the resonance originated not only on the coral reef, but also on the slope and island platform.

There is another phenomenon linked to the coral reef where the abrupt break of waves allows energy to be transfered to infra-gravity frequencies. to infra-gravity frequencies (Surf Beat), also causing an increase in the degree of flooding. One example was what happened during the Haiyan typhoon that hit Philippines on November 8, 2013 (Roeber and Bricker 2015).

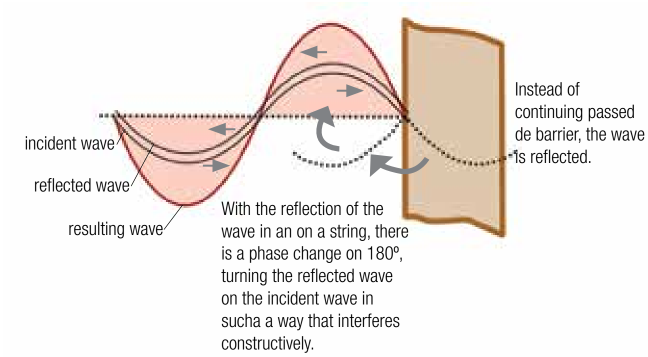


**Figure 20.** Representation of standing wave: the incident wave travels to find an obstruction. The reflected wave with the same characteristics of the incident wave travels in the opposite direction. The interaction is called resonance when is constructive (taken from Hyper-Physics, 2015).

**Figure 21.** Above, boat taken from the sea by tsunami waves in Fagotogo Bote. Center, people walk down the still flooded street in Pago Pago; American Samoa September 29, 2009 (taken from National Geographic News, 2015). Down, destructions in the parking of Pago Plaza, American Samoa photo of Gordon Yamasaki (taken from USGS, 2015).

In order to understand the phenomenon, researchers used a model with averaged phases that do not take into account the interaction that groups of waves of different period and height may cause. This type of model is often used in the United States for risk assessment in coastal area (Roeber and Bricker 2015). The model could reconstruct with precision the rank of flo oding in Tacloban (Figure 22), one of the most affected cities. Strong winds caused by typhoon combined with the morphology and location of the city, caused major flooding, up to 6 m. However, the model underestimated the flood of another town, Hernani. Consequently, a model Bosz (Boussinesq-Type phase-resolving wave model) was implemented to solve or estimate the interaction between groups, individual waves and slope *surf beat*.

The model Bosz allowed to reproduce the phenomenon occurred in Hernani, in addition to identify the phenomenon involved. In this case the flood was caused by the abrupt breaking of waves under the barrier reef. Causing exacerbation of surf beat, producing a higher degree of flooding. In fact, the worst scenario would be that these two phenomenon would occur at the same time: exacerbation due to resonance and due to wave breaking over the reef (Roeber and Bricker 2015). More detailed analysis with the Bosz model show that the reef has a protective effect of storms up to halfway the typhoon Haiyan (Roeber and Bricker 2015).

In a similar way, the barrier reef of Puerto Morelos can increase or decrease flood risks depending on the morphology of the lagoon and the incident swell (Torres-Freyermuth et al. 2012). The lagoon of Puerto Morelos, to some extent, has a wide range of morphological conditions. The 4 km of coral reef bordering the lagoon which widht varies from 1500 m, in the far North to 500 m to the far South. Besides the depth of the barrier reef is between 5.3 and 0 m (Torres-Freyermuth et al. 2012). Such range of characteristics implies that the same wave conditions, can have differential responses along the lagoon.

In the case of resonance phenomenon, it has been found that it is more likely to occur in the extreme South, because the oscilation period is equivalent to the period of the infra-gravity waves generated in the area (Table 2). Meanwhile the width in the Northern zone seems to avoid this phenomen, at least for the wave conditions used in the model (T between 6 and 14; Hs between 2 and 7 m) (Torres-Freyermuth et al. 2012). However, the model implemented is one-dimensional, meaning that it used paths perpendicular to the coast (Figure 23). Therefore, the same authors recommend the implementation of model 2 D to enrich the results (Torres-Freyermuth et al. 2012).

Contrary to Hernani (Philippines), Puerto Morelos has a barrier reef where infra-gravity waves can even break (Franklin 2015), so that, what happened in the Philippines is unlikely. In fact, in this case the reef would fulfill a protective function, dissipating the energy of these waves.

Table 2. **Periods of oscillation calculated by Kowalik and Murty (1993) (taken from Torres-Freyermuth et al. 2012.)**

| *Profiles* | *To (s)* | *T1(s)* | *T2(s)* |
|---|---|---|---|
| P0 | 639 | 213 | 128 |
| P1 | 1122 | 374 | 224 |
| P2 | 1326 | 442 | 265 |
| P3 | 1605 | 535 | 321 |

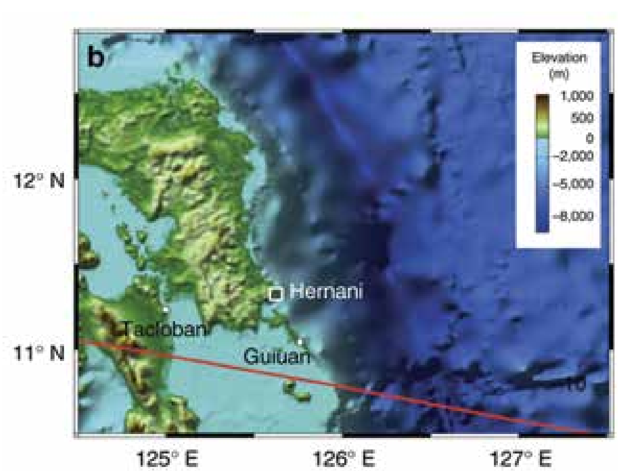


**Figure 22.** Location of Hernani and Tacloban, the red line represents the path of Typhoon Haiyan (Yolanda) (taken from Roeber and Bricker 2015).

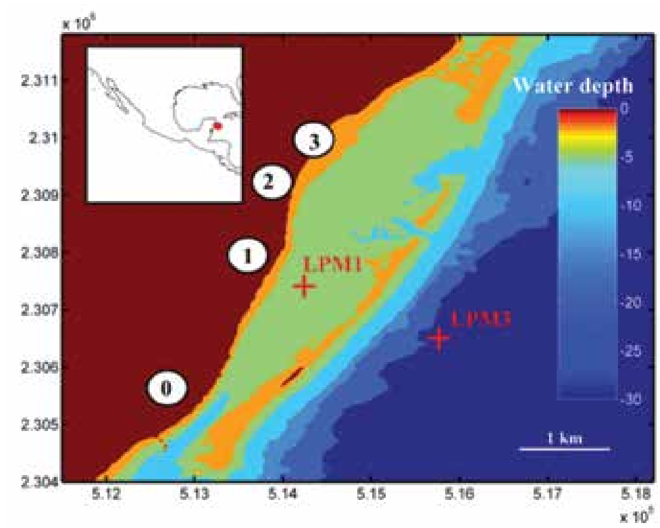


**Figure 23.** Location of the evaluated profiles in Puerto Morelos (taken from Torres-Freyermuth et al. 2012).

## Conclusión

The knowledge of the regional geo-morphology is crucial to assess the risk of flooding. The interpretation of these risks, does not imply the devaluation of the barrier reef as coastal zone protection. Phenomenon such as resonance can also be caused by the slope and insular or continental platform. Just these examples warn us that if these variables are not taken into account, can lead to an underestimation of the risk of flooding. Therefore, it is advisable to use models to solve or evaluate the phase of the incident wave, not to omit phenomenon like the interaction energy of wave breaking and Surfbeat. In the case of Puerto Morelos, differential responses can occur along the lagoon due to the range of conditions that provide the coral reef. Therefore, further studies should involve these conditions and preferably two-dimensional models.

Torres-Freyermuth et al. 2012 Methodology

SWASH model open source was used, developed by the University of Technology in Delf. The validation was made from a laboratory experiment from Demirbilek et al. 2007 and based on field observations in Puerto Morelos Coronado et al. 2007. The implementation was done in four profiles (one-dimensional) distributed along the lagoon (Figure 23), up to 20 meters deep and using a synthetic wave of JONSWAP type. The range of wave conditions was Hs 2 to 7 meters and periods of 6-14 s.

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## 1.4 The barrier reef favorable differential in the height of the water column between the inner and outer level of the reef lagoon; encouraging flows within and outside the lagoon (open sea), which keep the flow of nutrients and pollutants

The circulation inside a system of reef lagoon is dominated by the incident wave (Lowe et al. 2010, Taskjelle et al. 2014). This generates an over elevation of the mean sea level, called *setup* that causes the flow through the reef, towards the coast, due to the height difference that occurs between the surf zone and lagoon ($\eta_L$), see Figure 24 and Figure 25 (Lowe et al. 2010). In the map view (Figure 24, right) you can see the movement through the channels of the reef lagoon. This process balances the water levels of the sea and the lagoon. It is a complex system in which various aspects can be considered:

1. Morphology of the reef: front reef slope, width of the reef plain, crest height, roughness of the reef and its location at the waterfront.
2. Morphology of the lagoon: lagoon depth and width of the channels.
3. Wave and tide conditions (Taskjelle et al. 2014, Enriquez et al. 2014).

These variables are independent for instance, the importance of reef morphology in lagoon circulation, will depend on the lagoon morphology. In fact, in order to exclude its circulation effect, the lagoon should have a depth up to 10% of the extent of the reef lagoon; on the other hand, to exclude the effect of the channels, these should have the same width that the barrier reef. These conditions are excluded on the reef edge.

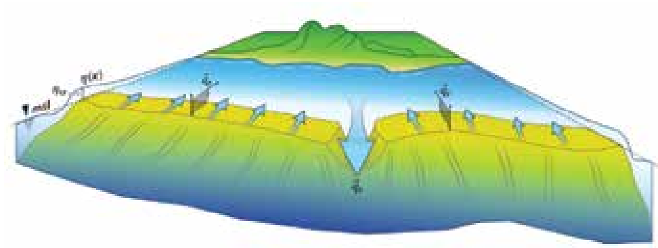

**Figure 25.** Front view of a lagoon system delimited by the barrier reef. As in Figure 1, the wave generates a flow (qr) into the lagoon and over the water elevation (η) from the mean sea level (msl); simplifying the amount of water entering the lagoon by flows gr, it must be compensated by the amount of water outgoing through the flow mouth (qc), (taken from Lowe and Falter, 2015).

In the case of Puerto Morelos, the lagoon has widths between 500 and 1500 m, with an average depth of ~ 4 m (Coronado et al. 2007) amounts to less than 1% of the width of the reef platform, so the role of the lagoon in the circulation cannot be excluded. Regarding the barrier reef, it has been observed that its influence is greater when it is closer to the coastline and decreases as the lagoon reaches its greatest width (Ruiz de Alegria-Arzaburu et al. 2013).

As to the hydrodynamics, it has been observed that the circulation is dominated by the incident swell (Coronado et al. 2012; Enriquez et al. 2012). The area is micro-tidal with a tidal range ranging from 7-32 cm, so its role in the circulation is not important.Tides can generate Southwest residual currents with a speed less of 0.008 m/s. In the case of winds with Northeast-East direction can increase the set-up. Winds with Southeast direction generate North-bound currents (Enriquez et al. 2012).

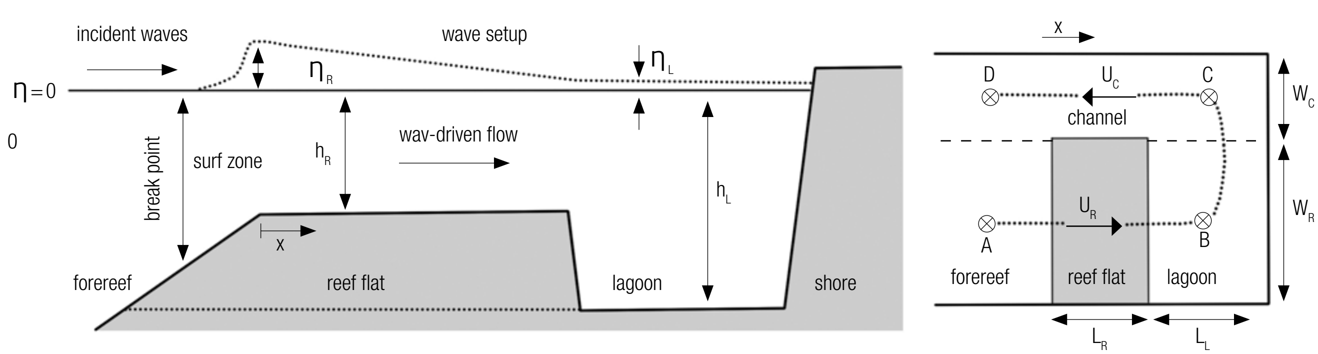


**Figure 24.** Lagoon circulation, left, transversal section; right, superficial view (map view) (taken from Lowe et al. 2010).

It is interesting that for this lagoon, there is one more variable to consider, the Yucatan Current which influences the circulation as it affects the water level in the area. When the Yucatan Current intensifies, the water level in front of the lagoon decreases. This phenomenon reduces the incident wave energy because that the surf zone is shifted offshore. This shift increases the distance that the waves have to go through over the reef, which increases the friction effect and therefore the dissipation of the swell. In addition, the friction from the seabed and the reef are intensified due to the decrease in the average sea level (Coronado et al. 2007).

Particularly in Puerto Morelos, the effect of roughness on the elevation produced or setup, using numerical modeling (Franklin et al. 2013), has been studied. It was found that setup decreases as the roughness of the reef reduces. As we observed, this is an important part of the mechanism of lagoon circulation, its decline could be reflected in a lethargy of circulation and greater times of residence. The residence time in a reef lagoon increases exposure to pollutants and the possibility to reach higher local temperatures due to solar radiation (Franklin et al. 2013). However, studies are needed to corroborate these results.

## Conclusion

The dominant factor of the lagoon circulation in Puerto Morelos is the swell. Its influence is modified by the morphological characteristics of the barrier reef and lagoon. There is also indirect modulation of the Yucatan Current. And it has been found that the loss of roughness could be considered important, generating longer residence times. However, more studies are needed to weight the importance of each factor involved.

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## 1.5 **Continuous anthropogenic pressure leads to degradation of coral and the decrease of growth rate compromising the reef structure**

### Caribbean reefs have lost their complexity and reef structure

The reef complex in the Caribbean has decreased dramatically since the 60's. For 2009, 75% of coral communities have very low levels of roughness (less than 1.5) and virtually all coral communities with high roughness have disappeared (higher rates than 2), Figure 26 and Figure 27 (Alvarez-Filip et al. 2009).

The physical structure and complexity of the reef system are necessary to maintain the lagoon's hydrodynamics and reduce wave energy. Therefore, the loss of roughness changes the hydrodynamics of the lagoon, increases sediment transport and reduces the service in coastal protection (Alvarez-Filip et al. 2009; Ruiz de Alegria-Arzaburu et al. 2013; Alvarez-Filip et al. 2015).

The loss of roughness leads to the loss of complexity; the complexity is necessary to maintain the high biodiversity of coral ecosystems because complexity provides shelter to fish and invertebrates from predators and to environmental stressors. The loss of complexity disturbs fish and invertebrates life cycles, reducing richness, abundance and biomass of species and the viability of fisheries (Alvarez-Filip et al. 2009; Ruiz de Alegria-Arzaburu et al. 2013; Alvarez-Filip et al. 2015).

The determining phenomena of reef degradation suffered in the Caribbean are (Kennedy et al. 2013):

- The reef fish were overfished in the 60's and 70's; without predators, the sea urchins expanded rapidly. This over-population damaged the reefs by causing bio-erosion of corals, except for the places where there was a high abundance of coralline algae (greater coverage to 55%) in which case the algae growth was controlled by sea urchins.

- Strong outbreaks of the white band occurred in the 70' and 80' which caused a drastic reduction of *Acropora palmata* and *Acropora cervicornis*, important species in the formation of the reef (Alvarez-Filip et al. 2009 species. Kennedy et al. 2013).

- Between 1983-1984, occurred a massive reduction in sea urchins, *Diadema antillarum*, probably related to an infectious disease. Algae, without their natural predators (reef fish and sea urchins) began to increase its presence and gain space on the coral (Blanchon et al. 2010).

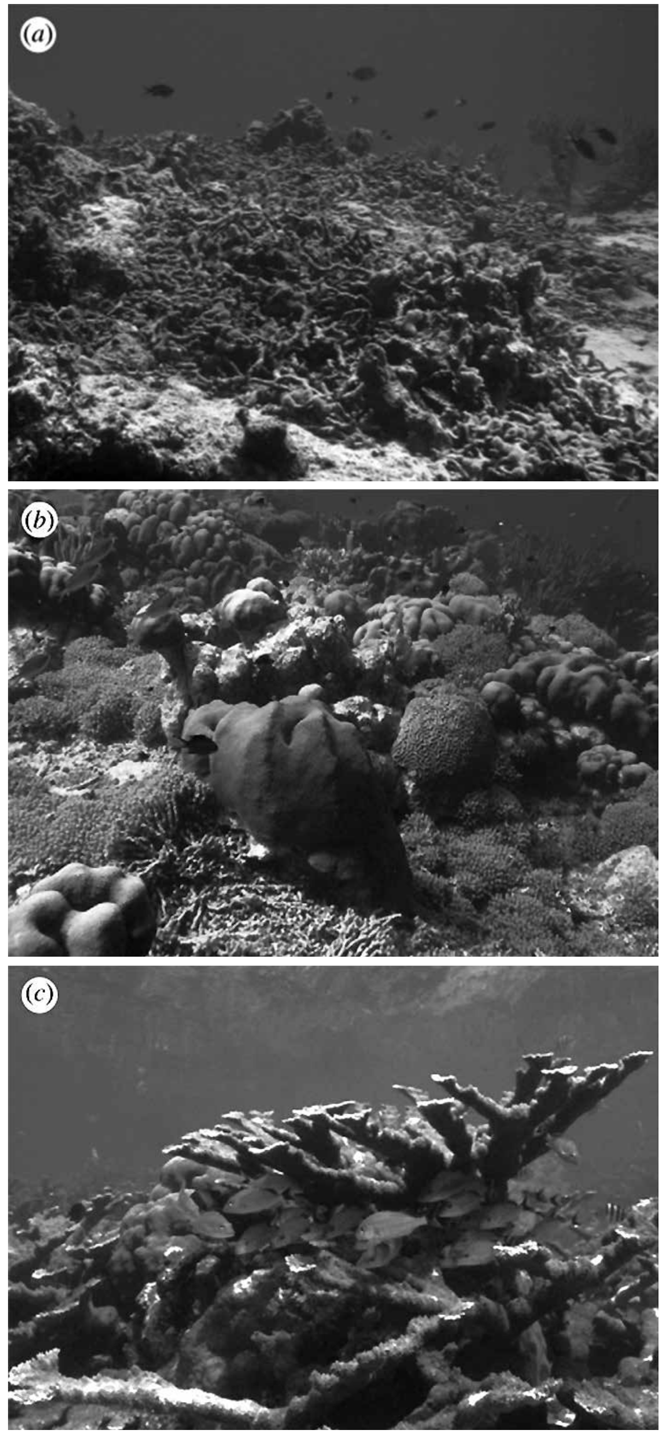


**Figure 26.** Example of three values , of roughness index in the Caribbean reefs: a] 1.2 b] and 1.5 c] 2.5. This roughness index is one of the most widely used methods to express the structural complexity of the coral, it is obtained from the relation between the total length of a chain and the length of the coral when spread over the surface of interest (Risk 1972). The value ranges go from 1 being a completely flat surface up to 3 to a coral with great structural complexity, although, higher values may exist, they are not usually common (Alvarez Filip et al. 2009). Photos L. Alvarez-Filip, M. Uyarra and M. Henry (taken from Alvarez-Filip et al. 2009).

- Two severe bleaching events caused high mortality in corals in 1998 and 2005; since 1998 corals bleaching have been increasingly frequent (Alvarez-Filip et al. 2009) due to the prevailing increase in surface temperature of the sea.

- Particularly in Puerto Morelos, Hurricane Gilbert (1988) caused a reduction of stony coral from 16 to 12 and coral cover from 8.4% to 3.1% (Rodriguez-Martinez et al. 2010).

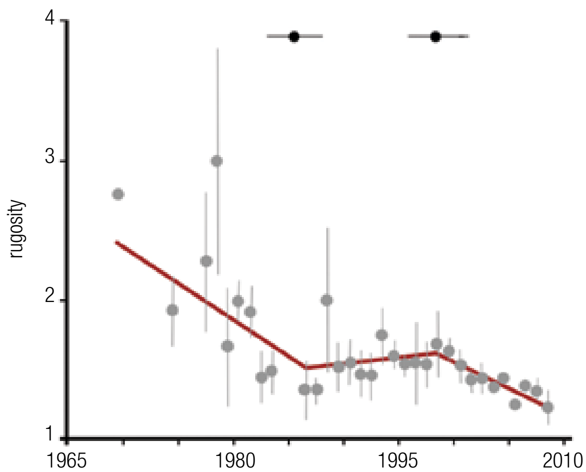


**Figure 27.** Changes in reefs roughness in the Caribbean between 1969 and 2008. [black line] set Model (mean +/- confidence intervals). The slopes from 1969 to 1984, from 1985 to 1997 and from 1998 to 2008 are -0054, 0.008 and -0038, respectively. The black dots on the top of the graph indicate significant turning points, 1985 and 1998 (taken from Alvarez-Filip et al. 2009).

### *The calcification process is essential for maintaining the structural complexity and the reef*

The calcification is a physiological process that forms part of the coral growth that determines the size and complexity of the coral communities. The balance of the calcification indicates if a coral is in accretion or disintegration stage. The calcification needs energy and for that the environmental conditions must be appropiate in order that the corals can use their energy to create a skeleton and not to attack diseases or competing with algae, among others. The variables that determine the rate of calcification are luminosity, saturation of carbon in the water, turbidity, exposure to waves, the rate of reproduction of corals and the water temperature (Adame et al. 2012).

To ensure that the structure and complexity of the reef is maintained, it is necessary that the calcification rate be greater than the rate of erosion (Kennedy et al. 2013). If the coral does not have the ability to build its skeleton (accretion) may not recover from environmental and mechanical damage suffered (erosion). Those processes that limit the rate of calcification of corals and events that result in the decrease of coral cover can seriously compromise the reef structure (Blanchon et al. 2010). For example, in Puerto Morelos Hurricane Gilbert (1988) caused a reduction of species from 16% to 12% of stony corals and 8.4% to 3.1% in coral cover (Rodriguez-Martinez et al. 2010). Monitoring during 12 years in Puerto Morelos (1993-2005, Rodriguez-Martinez et al. 2010) show that until 2010, the recovery of coral communities has been precarious, indicating little resilience to such phenomenon. The coral community seems to be blocked in an early stage of development. Coral cover is very low (3%) and has a relatively high density of colonies smaller to 10 cm (75%), which indicates the existence of a high recruitment but with low survival rates and low probability of achieving larger sizes (Rodriguez-Martinez et al. 2010). By contrast, the communities of seagrasses, gorgonians (soft corals) and algae show greater resilience and in particular the latter have won the hard coral surface (Rodriguez-Martinez et al. 2010).

Some authors suggest that coral communities will not collapse but there will be a replacement for more resilient species (Hughes et al. 2012) because not all species respond the same way to climate change. For example, *Porites astreoides* is now one of the species most widely distributed in the Caribbean and has increased its relative coverage (total coral cover/*P. astreoides* coverage) from 20% to 50% between 1970 and 2003. However, *P. astreoides* has maintained its historical coverage because of their resistance to adverse conditions while another species have declined or disappeared (Green et al. 2008).

Alvarez-Filip et al. (2013) showed that coral species that can survive the new conditions with higher temperature and acidity will not be able to hold neither the structure or the complexity of the reef, even if the coverage is maintained. Species with high reproductive rates are also the most resistant to environmental changes; however, often they generate small colonies that contribute little to the accretion of the reef. Meanwhile the massive colonies of coral reefs are often susceptible to environmental variables (Alvarez-Filip et al. 2013). Modeling Alvarez-Filip et al. (2013) shows that the coral species replacement will result in a rapid loss of the rate of calcification and reef roughness even though the total abundance of live coral does not change (Figure 28). Alvarez-Filip modeled changes in reef complexity with four reef-forming species, *Acropora* (*A. palmate* + *A. cervicornis*) and *Orbicella* (*O. annularis* + *O. faveolata*) and two competitive species with smaller and less complex colonies, *Porites astreoides* and *Agaricia agaricites* (Table 3). *Acropora* loss is so important that even when a rapid recovery of other species was considered, it was not possible to

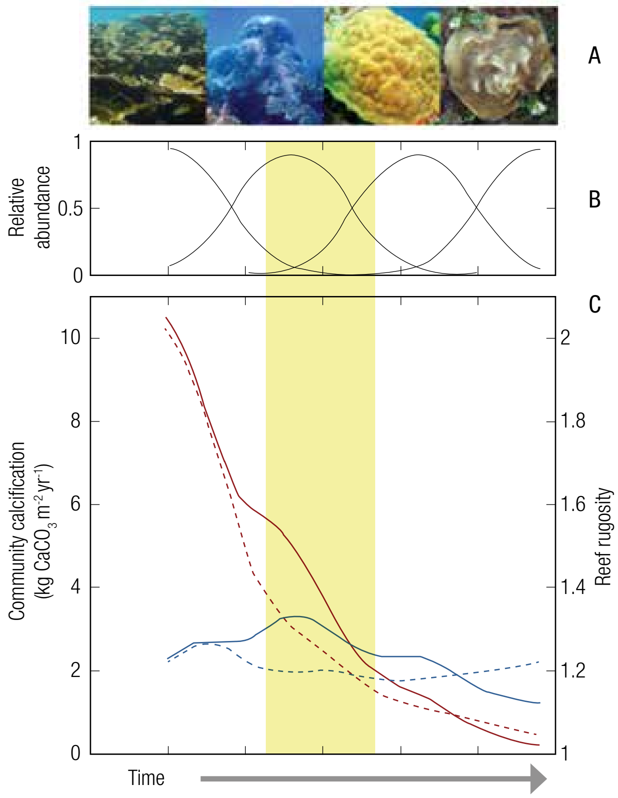


**Figure 28.** The turnover in coral assemblages results in rapid loss of coral community and the roughness of the reef. A] Images of colonies: from right to left, *Acropora*, *Orbicella*, *Porites*, *Agaricia*. B] Relative abundance vs time, the curves represent a succession of species: while the abundance of a species reduces, the succesor species increases, maintaining a constant relative abundance. C] Rate of calcification (solid lines) and reef roughness (dotted lines). Two possible scenarios are proposed that consider the uncertainty of the initial state of the coral: i] coverage of the declining coral from 45% to 10% (red line) and ii] recovery of coverage from 10% to 45% [blue lines]; the yellow band represents the current condition of Caribbean reefs (taken from Alvarez-Filip et al. 2013).

### Alvarez-Filip 2013 Methodology

A model was implemented to estimate the effect of species turnover. Reef forming species, *Acropora* (*A. palmata* + *A. cervicornis*) and *Orbicella* (*O. annularis* + *O. faveolata*), were used and competitive species with smaller and less complex colonies, Porites astreoides and Agaricia agaricites. Gauss curves were used to simulate the abundance of each specie and were overlapped so that the relative abundance was always the same, when the abundance of a specie begins to decline, the new one begins to dominate (Figure 28, A). The succession of species was established according to the rate of calcification (Table 3), which was calculated in Puerto Morelos, Mexico. At each point the rate of calcification and roughness was evaluated.

recover the rate of calcification nor the roughness. The study was done with calcification rates measures in Puerto Morelos.

The factors that have influenced the decrease of the accretion rate can be global as the increase in temperature and ocean acidification, like nutrient pollution and fishing herbivores (Kennedy et al. 2013).

Table 3. **Mean extension (cm/year), mean density (g/cm³), estimation of calcification rate, the calcification rate (kg/m² year) and mean roughness per colony. Number of samples in parenthesis (taken from Alvarez-Filip et al. 2013)**

| *Genus* | *TExtension rate (cm/year)* | *Density (g/cm³)* | *Calcification rate (kg/m²año)* | *Roughness rate* |
|---|---|---|---|---|
| *Acropora* | 8.84 +/- 4.33 | 1.88 +/- 0.26 | 22.30 | 3.33 +/- 1.31 (n=13) |
| *Orbicella* | 0.85 +/- 0.32 | 1.59 +/- 0.25 | 13.80 | 1.87 +/- 0.44 (n=46) |
| *Porites* | 0.41 +/- 0.13 | 1.48 +/- 0.16 | 6.12 | 1.49 +/- 0.40 (n=51) |
| *Agaricia* | 0.25 +/- 0.04 | 1.92 +/- 0.05 | 2.43 | 1.52 +/- 0.43 (n=73) |

### 1.5.1 The increase in the average sea temperature decreases the rate of coral calcification and increases the frequency and severity of coral bleaching, disease and hurricanes

The increase in sea temperature seriously affects the reef structure and causes adverse and severe impacts on corals such as increase in frequency and severy of coral bleaching (Blanchon et al. 2010), of coral diseases (Bruno et al. 2003), hurricanes (Webster et al. 2005) and decreases the rate of coral calcification (Kleypas et al. 2005; Carricart-Ganivet et al. 2012). In addition to the synergistic effect, while there are factors with a direct effect (hurricanes and bleaching), others may affect the resilience of coral (diseases and decline in calcification rate).

#### *Reduction of the calcification rate*

The optimum temperature for maximum rate of calcification is between 26 and 28° C (Norzagaray-López et al. 2014). Despite that there are regional variations, it is expected that corals calcification rate will decrease outside this temperature range. (Kleypas et al. 2005; Carricart-Ganivet 2012 et al.). The study made by Carricart-Ganivet et al. (2012) estimated that if the current temperature increases by 2100 the remaining species will lose their ability to calcify (*P. astreoides*) and others will be reduced to 40% (*Montastraea* spp). In fact, it is estimated that calcification cease at 30° C for *Porites* ssp. and at 35° C for *Montastrae* ssp. (Carricart-Ganiver et al., 2012).

Another important aspect is the adaptation strategies of different species of corals. When *Porite* spp is stressed reverses its energy to grow faster and reduces the rate of calcification causing a loss of surface area. In the other hand, *Montastrae* spp. maintains its accretion rate but reduces the density of the skeleton. Therefore, *Porite* spp. loses coverage and *Montastraes* spp becomes more susceptible to physical and biological disturbances (Carricart-Ganivet et al. 2012).

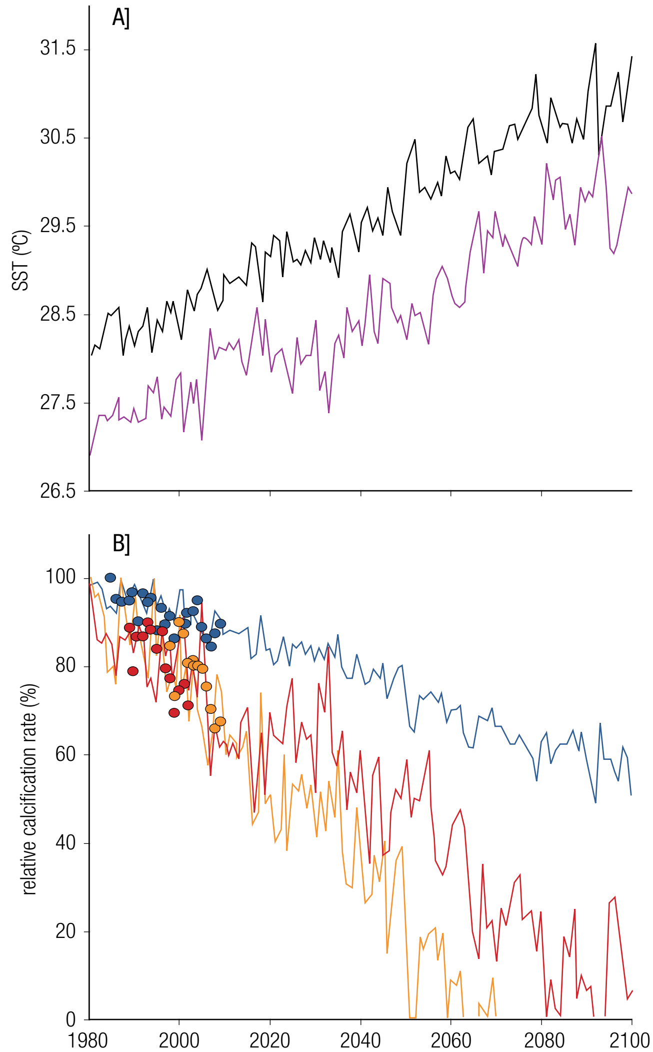


**Figure 29.** Modeling the sea surface temperature (SST) and calcification rate for *Porites* spp. and *Montastraea* spp. from 1980 to 2100. A] SST for the Great Barrier Reef (purple line) and the Caribbean (black line). B] Annual relative rate of calcification of *Porites* spp. (red line) in the Barrier Reef and *P. astreoides* (orange line) and *Montastraea* spp. (blue line) in the Mesoamerican Barrier Reef System (taken from Carricart-Ganivet et al. 2012).

Carricart-Ganivet et al. 2012 Methodology

Samples were taken from the Great Barrier Reef (Australia), reefs in Mahahual and Bancho Chincorro (Mexico, Mesoamerican Reef). The calcification rate was obtained from the product of annual growth and density of the skeleton. The SST was obtained from the Hadley Centre Sea Ice database and SST which is produced by the Meteorology office from UK. The aragonite saturation state was estimated by The National Acidification Product Suit (v = .5, NOAA). To estimate between 1980 and 2100 the Hoegh-Guldberg (1999) model was used and in the case of calcification a linear regression was used.

### *Frequency and severity on events of coral bleaching*

From the biological point of view coral bleaching is the breakdown of the symbiotic relationship between dinoflagellates (zooxanthellae) and their hosts (corals). Bleaching can be initiated by exposure to extreme environmental conditions of temperature, salinity and solar radiation (Blanchon et al. 2010). As temperature changes, the range of resistance to coral bleaching can change locally (Zhang et al. 2013; Norzagaray-López et al. 2014). In fact, a coral that has survived an event of high temperatures will be more resilient (Zhang et al. 2013). It has been determined that an increase of 1.5° C is required for a continuous period of 3 to 4 weeks above average summer temperature (regional) to cause coral bleaching (Balnchon et al. 2010; Hoegh-Guldberg 1999).

The biggest coral bleaching episodes are related to *El Niño* phenomenon because it causes an increase in sea surface temperature, Figure 30 (Hoegh-Guldberg 1999). Since 1982 there has been an increase in the severity, frequency and geographic scope in bleaching events (Figure 30). In 1998, mass events of coral bleaching all around the world were reported matching with the most severe *El Niño* ever recorded. In 2015-2016, it was estimated that 16% of the world coral cover has been lost (Hoegh-Gulberg 1999).

In Puerto Morelos the first recorded bleaching event was in 1995 and since then there has been bleaching whenever the temperature exceeds 30° C. The most severe cases were in 1995 and 2005 when more than 50% of the colonies showed bleaching with varying degrees of severity. In 1998 bleaching in the region was not as intense as in other parts of the Caribbean, however, observations may be biased due to the season in which the sample was taken (Rodriguez-Martinez et al. 2011).

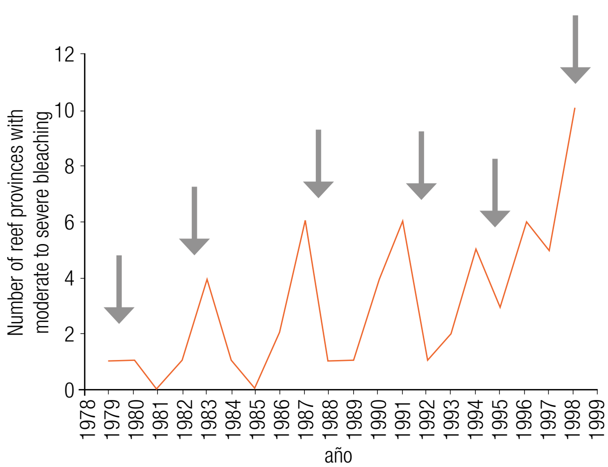


**Figure 30.** Number of provinces with bleaching since 1979. The arrows indicate the year in which the *El Niño* phenomenon was more severe (Hoegh-Guldberg taken et al. 1999).

### *Increased severity on diseases*

Rodriguez-Martinez et al. (2010) attributed the increase of diseases in Puerto Morelos to an increase in temperature. The mechanism involved is complex, however, it has been postulated that the increase in temperature reduces the ability of the coral to face diseases. Simultaneously, it favors the microorganisms involved in the development of populations, distribution and expansion; the change of the mutual interaction into a pathogenesis and a production of pathogenic metabolites (in some *Vibrios*) (Balnchon et al. 2010).

### *Occurrence of hurricanes*

Studies of hurricanes indicate that since the 70's there has been an increase in the intensity and frequency of hurricanes (Webster et al. 2005). The impact on coral communities is severe because the recovery of the damage after a hurricane may take decades or cause irreparable damages, as in the case of Gilberto (1988) in Puerto Morelos where live coral cover fell to 3% without signs of recovery (Rodriguez-Martinez et al. 2010).

## Conclusion

The increase in sea surface temperature affects seriously the reef structure. In addition to the effect of each factor, there is a synergetic effect that exacerbates the damage and accelerates the loss of structure and complexity and the degradation of the reef. Hurricanes and bleaching can cause serious damage in weeks, days or even hours. Meanwhile, diseases and a decreasing calcification rate do not allow corals recovery from these phenomenon, causing irreversible damage.

## 1.5.2 Ocean acidification has decreased the rate of calcification of corals in the Mexican Caribbean

As a result of human activities, the atmospheric concentration of $CO_2$ in 2008 exceeded 380 ppm, which represents 80 ppm above records at least 74,000 years ago. During the 20th century the increase of atmospheric $CO_2$ has caused an increase of 0.74° C in atmospheric temperature, 17cm of sea level and 0.1 units of global pH of sea, along with a decrease in the concentration of calcium carbonate in the ocean of ~30 micro moles kg-1 (Hoegh-Gulberg et al. 2008). Because the coral calcification requires the presence of carbonate in seawater, Hoegh-Gulberg et al. (2008) estimate that corals will reduce growth by 40% when they reach 560 ppm (twice the concentration of the pre-industrial era).

It is estimated that approximately 25% of the $CO_2$ emitted into the atmosphere is captured by the ocean where it reacts with water to form carbonic acid and hydrogen; this latter can react with dissolved carbonate limiting their availability for biological systems (Figure 31). Aragonite is one of the most soluble forms of calcium carbonate and is widely used by corals. The coral requires basic pH and high aragonite saturation (higher levels to 3Ω)[3] for its calcification (Norzagaray-López et al. 2014). Aragonite saturation levels less than 3Ω cause stress to corals and levels below 1Ω cause that coral structures begin to dissolve (NOAA 2016).

Studies in the Mexican Caribbean have not detected a change in calcification due to changes in aragonite saturation. However, authors recognize that their database is limited in time (2003-2010) and have not included all species, also the calcification process is complex so the effect of aragonite may be masked by other factors.

Crook et al. (2012) studied the effect of groundwater discharges on Puerto Morelos (waterholes) which typically have low acidic pH and carbonate saturation. Through observations, they found that there are species that can survive in these conditions, but they are limited with respect to which can be found in the vicinity. The extreme conditions found in Puerto Morelos show that there are species that can tolerate and even keep its calcification in these acidic conditions. These corals have continually been subjected to this stress which may have forced them to adapt to it. The energy needed for calcification may come from reducing other metabolic activities, which may be causing a slower growth rate or more susceptibility to physical and biological agents (Crook et al. 2012; Carricart-Ganivet et al. 2012).

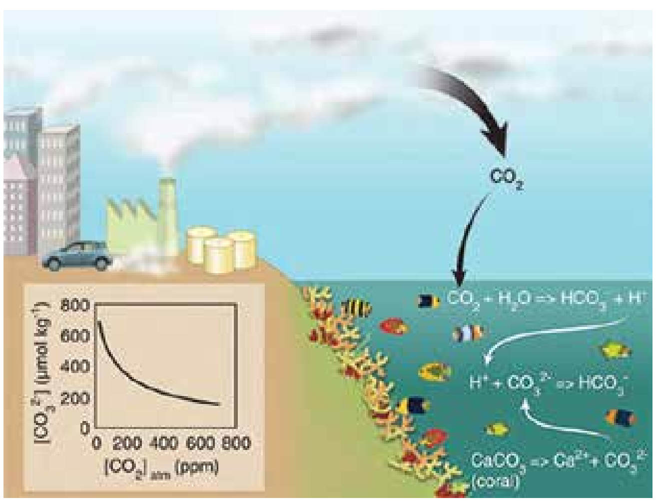


**Figure 31.** Interaction between the increase in atmospheric $CO_2$ and $CO_3^2$ dissolved. Approximately 25% of atmospheric $CO_2$ is absorbed by the ocean. This breakdown upon contact with water forming carbonic acid and hydrogen. Hydrogen is able to react with dissolved carbonate, limiting their availability for the formation of coralline structures (taken from Hoegh-Gulberg et al. 2008).

Finally, the authors suggest that: "under the saturation degree of actual carbonates (2.5Ω) the species that dominate the reef construction in the Mesoamerican Reef as Acropora and Montastraea, could be replaced by small reef patches with fewer species" (Crook et al. 2012).

## Conclusion

The Aragonite saturation in the Caribbean threatens the structural stability of the reef. It cannot exempt Mexico from this risk, even though there are not submitted convincing evidence. It is suggested that stress caused by the decrease of aragonite could compromise other metabolic functions making the coral more susceptible to disease and fragile to mechanical damage.

## 1.5.3 The water pollution comes from anthropogenic activities and affects reef promoting or exacerbating coral diseases

Water pollution of anthropogenic origin can seriously affect coral systems. The wastewater can reduce levels of calcification, photosynthesis, recruitment and reproduction of corals, increase their susceptibility to diseases and even promote greater abundance of competitors (Fabricius 2005; Baker 2013).

The first step is to determine if the nutrients that affect corals are of anthropogenic origin and not from natural sources. In the case of Yucatan Peninsula it is more complex due to the karst soil and groundwater circulation system where various interconnections exist.

The coastal aquifer can be divided into three areas: 1] water lens, between 10 m and 100 m in thickness and forms the upper band; 2] saline water zone constituted by a lower band to fresh water and can enter up to 100 km in land (saline intrusion) and the mixing zone (Figure 33 and Figure 36) (Null et al. 2014). The legislation allows the use of saline water zone for sewage water deposit, because it is believed that water will be confined for years or decades and its influence on marine communities will be limited (Beddows et al. 2007). However, research in the Yucatan Peninsula (Baker et al. 2007; Baker et al. 2010; Baker et. al 2013; Beddows et al. 2010 and Hernández-Terrones 2011) indicates that good connectivity and high rate of mixing aquifer cause the discharge of wastewater to contaminate fresh water and reach the sea.

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[3] The aragonite saturation state is defined as the product of the concentrations of calcium Ions $[Ca^2+]$ and Carbonates $[CO_3^{2-}]$ dissolved in the sea, divided between the aragonite solubility in seawater $[CaCO_3]$ (SOEST 2016).

$$([Ca^{2+}] \times [CO_3^{2-}])/[CaCO_3] = \Omega$$

Crook et al. 2012 Methodology

The areas of influence of groundwater discharge were determined by direct measurement of temperature, salinity and pH. For circular filtration the water samples were collected at intervals of 25 cm, intersecting the waterhole and covering up to 4 m out of this (Figure 32). In the case of fractures, samples were collected along paths up to 10 m following the fracture and in five or more perpendicular routes from it. The water was collected in syringes. Quadrants of 0.25 X 0.25 m were used along routes to select areas where the size and position of corals was measured. The dissolved inorganic carbon and the alkalinity were measured by analytical techniques (coulometry and potentiometry respectively). The presence of nitrate, nitrite, ammonium and phosphate are also quantified.

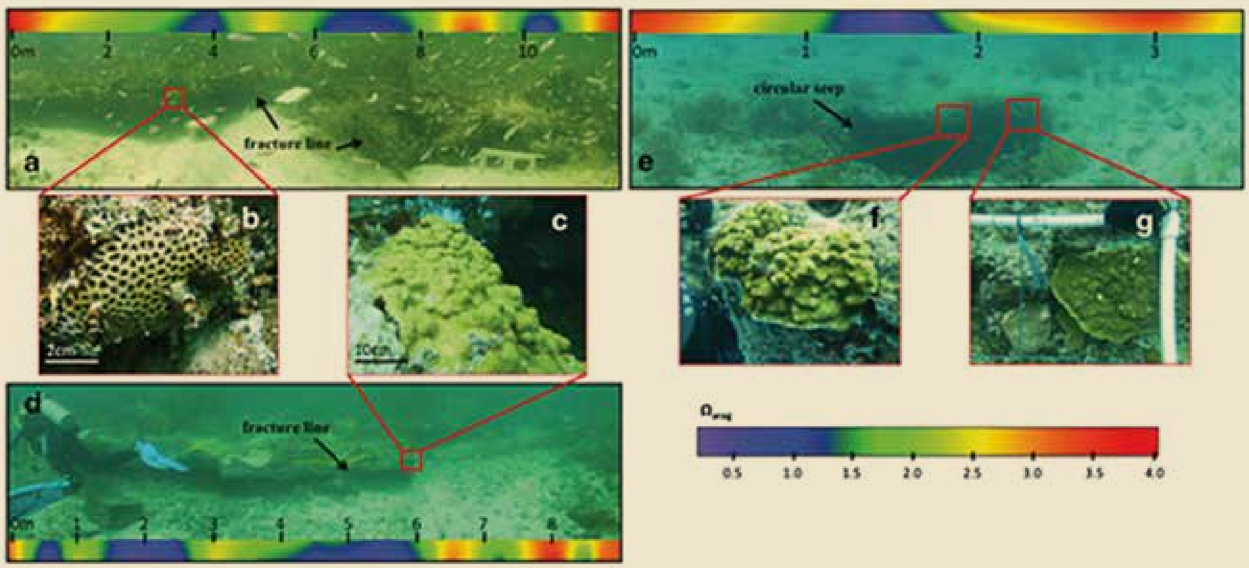



**Figure 32.** Distribution of aragonite saturation in the area of Influence of waterholes. The saturation is shown in colors: low saturation (0.5 Ω) in blue and super saturation (4.0 Ω) in red. Two examples of fractures: a] and d] a waterhole, e] and colonies of coral found near the eyes, b] *Siderastrea radians*, c, f] *Porites astreoides,* g] *Agaricia* (taken from Crook et al. 2012).

Beddows et al. (2003) proposed that the water flows through a system of caves and crevices connecting with wells, cenotes, wetlands and coasts, where the water is discharged through submarine springs (waterholes) located in the reef lagoon. Therefore, the fresh water aquifer interacts actively with coastal environments. Hernandez-Terrones et al. (2011) analyzed the temperature, nutrients, salinity, and the concentration of active silicon and coliforms (total and fecal) of various coastal and terrestrial environments (beaches, mangroves, cenotes, underwater springs, reef lagoon and the open sea) to determine this relation. The study site encompassed the sea, the lagoon, and around Puerto Morelos.

The results indicate the close interconnection between coastal systems and active mixing between freshwater and marine. 1] Increasing salinity gradients and decreasing dissolved silicon of wells seaward (Figure 35) show that the two water bodies exchange compounds in the opposite direction (Hernández-Terrones et al. 2011). Seawater (higher salinity) moves inland and fresh water (greater concentration of dissolved silicon) moves seaward. 2] Temperature values stand out connectivity

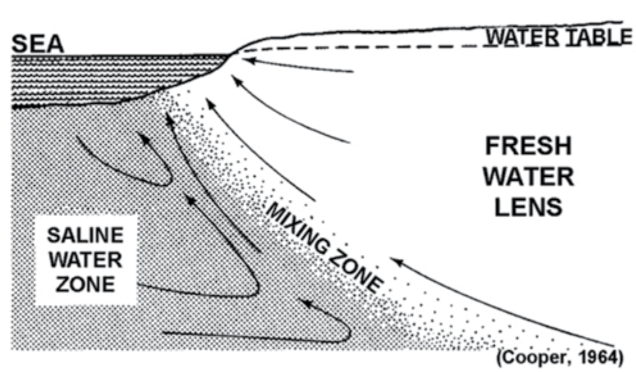



**Figure 33.** Diagram of aquifer (taken from Beddows et al. 2007).

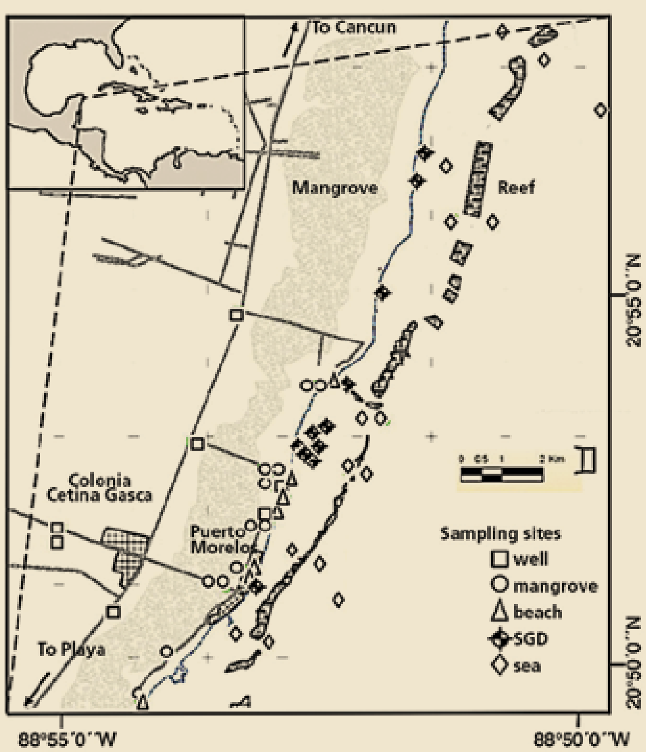
between wells and submarine springs. The water temperature in wells (~ 26° C) increases as it is more exposed to solar radiation in the mangroves, beaches, reef lagoon and the open sea (up to ~29° C). However underwater springs (water eyes) present at the reef lagoon maintain a similar temperature as in the wells (Hernandez-Lumps et al. 2011) indicating a direct flow of the inner aquifer towards the sea. Another result that suggests a direct connection between the inner aquifer and waterholes at sea, is that there has been found that fluctuations in the level of some cenotes correspond to tidal variations at distances up to 20 km from the coastline (Gastelú-Bárcena 2015; Rebolledo-Vieyra, personal communication February 2016).

The retention time of wastewater discharges in saltwater zone could be very limited because there is a dynamic mix of fresh and salt water in a distance of 4 km inland from the coastline; it can reach up to 10 km affecting wells and cenotes (Beddows et al. 2007). The conventional model of groundwater flow provides a slow flow of surface water, however, the temperature of the saltwater area decreases inland indicating that there is a mixture and a rapid flow of fresh water seaward (Beddows et al. 2007). In the conventional model this phenomenon would cause a gradual salination of fresh water on its way to the sea. However, in the Yucatan Peninsula it was found that the first 4 km have a high rate of mixing. The mixture is probably due to the movement induced by the tide and the turbulence caused by the collision with obstacles found in the ducts. As the distance from the coast increases beyond 4 km. mixture decreases and fresh water lens can be isolated (Beddows et al. 2007).

For all these reasons it is expected that discharges of waste water or pollution in the salt water zone will contaminate the lens of freshwater and coastal environments (Hernandez-Terrones et al. 2011; Redding et al. 2013; Beddows et al. 2007). Consequently, the flow and destination of wastewater discharge could be determined by the presence of pathogens and nutrients (nitrogen, phosphorus, etc.) in such environments. Hernandez-Lumps et al. (2011) determined that water in the wells has an excess of 80% of nitrogen of the permitted limit for human comsuption. Similarly, they found a large number of fecal coliforms in mangroves (125.4 colony forming units [CFU] / 100 mL) and underground water discharges (679.9 CFU / 100 mL). These levels probably indicate the percolation of sewage into the freshwater lens and the seaward (Hernandez-Terrones et al. 2011).

The values of nutrients and coliforms were quite variable, which show a local influence rather than regional; mangroves close to hotels showed higher coliforms concentration than other sites (Hernandez-Terrones et al. 2011).

Because nitrogen is also produced by natural means, it is necessary to distinguish between natural sources and anthropogenic sources. The isotopy has shown to be effective for




Hernández-Terrones et al. 2011 Methodology

Samples in duplicates were collected from 53 sites distributed in different environments: mangroves, wells, sand, underwater springs (waterholes), coastal lagoons and the open sea (Figure 34). Samples in the water table of wells and on the beach and at the surface level in the lagoon, sea and springs were also collected. Also. the water temperature, salinity, conductivity and pH were measured *in situ* using a *hydro lab DS5*. Analysis of nitrates, nitrites, soluble reactive phosphorus, soluble reactive silicon, phosphorus and nitrogen (total and organic); and of the presence of total and fecal coliforms were made. Finally, the submarine offshore flow was calculated by the method of Smith et al. (1999).

**Figure 34.** Sampling by Hernández-Terrones et al. 2011.

tracking wastewater (Baker et al. 2013), and could determine the source of nitrogen. Newly fixed nitrogen (natural means) contains an amount of δ15 N of -3 to 0‰ (parts per thousand) while the DIN (dissolved inorganic nitrogen) from wastewater contains between 6 and 22‰. Wastewater enriched with δ15 N indicate the presence of DIN derived from ammonia volatilization, the denitrification and nitrification of ammonium (Rico 2014).

The isotopy nitrogen was successfully used by Baker et al. (2013) to relate the degree of development with the nitrogen quantity to which the corals were exposed. The comparison was made between coral samples in front of two villages with different levels of development and tourist occupation, Mahahual and Akumal, but with a similar number of people (920 and 1362 respectively). Akumal has a major hotel development and between 2005 and 2009 hosted at 29% hotel state tourism; Mahahual is less developed and hosted only 5% in the same period (Baker et al. 2013). Also, Mahahual has a municipality treatment plant that processes 100% of wastewater from tourism development, while Akumal does not have a system for water treatment and wastewater is discharged directly into wells. The results show that the coral reef in front of Akumal has over 1.2‰ more isotopes (δ15 N) than Mahahual samples (Figure 37) indicating its anthropogenic origin.

A clear and important result of the study was the relation of isotopes in the coral and the number of tourists in the town. This relationship has an annual difference, that is, the number of tourists is reflected a year later in the composition of the reef. Between 2006 and 2009 there was a decrease of 37% in the number of tourists in Akumal which generated a reduction of 1.6% in the amount of isotope δ15 N . When levels of tourism recovered in 2009 an increase of N δ15 a year later, was found.

In the case of Puerto Morelos, it is known that there is a deficit in the treatment of wastewater; for example, in 2010, out

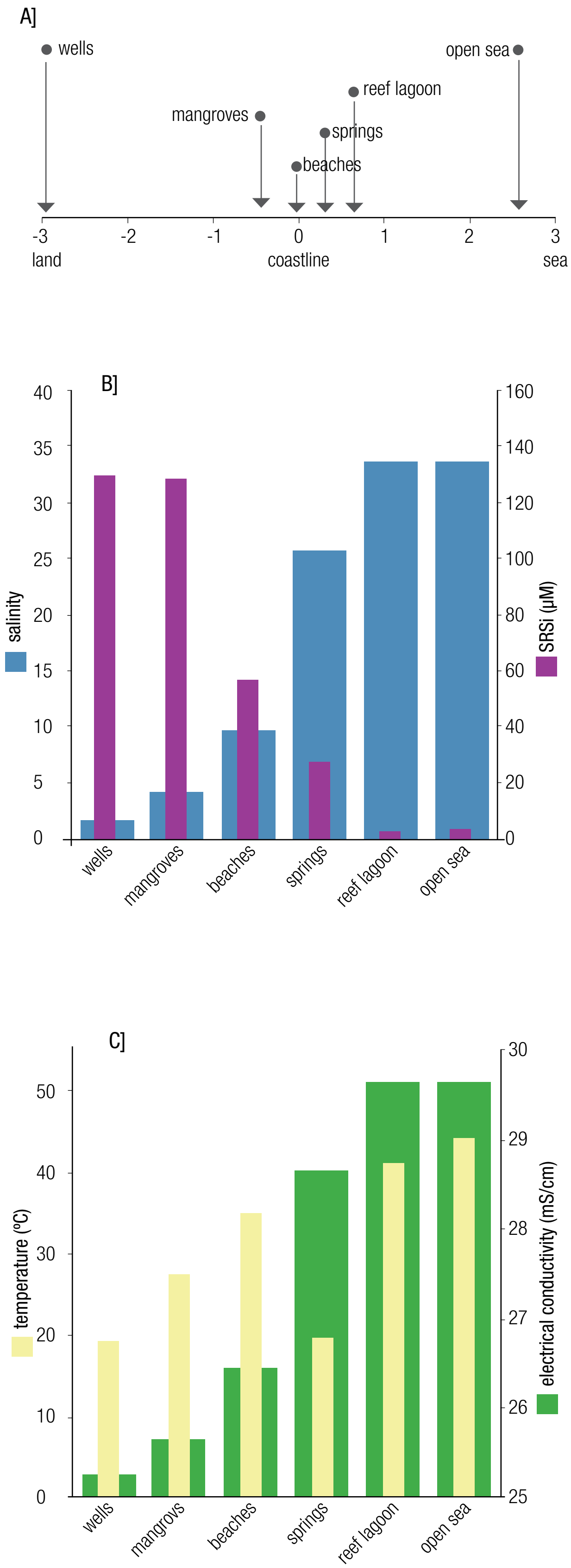



**Figure 35.** Results of sampling through the different wells environment, mangroves, beaches, springs, reef lagoon and the open sea. A] Average distance between environments, using as a benchmark the waterfront (0). The histograms represent the mean and the error bars the standard deviation: B] dissolved reactive silicon (SRSI, micromolar, pink) and salinity (S, turquoise); C] temperature (T, ° C, yellow), electrical conductivity (EC, mS cm -1, green). The gradual increase or decrease of the variables indicate connectivity and flow of water between environments, while the correlation between wells and springs temperature, stand out the close connection in the last ones (taken from Hernández et al. 2011).

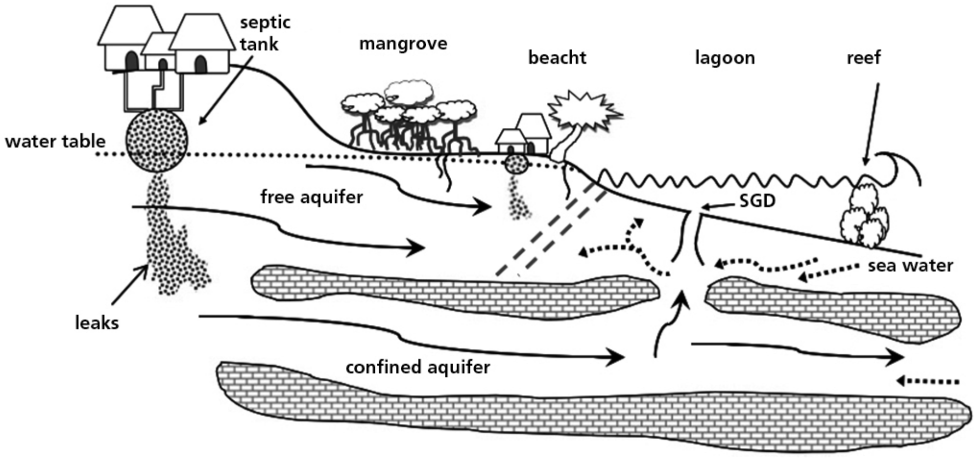



**Figure 36.** Diagram of aquifer and interpretation of Hernández-Terrones et al. (2011) of system interactions. The waste water and filtration from the city and tourism development reach the aquifer where they are transported to the sea, on their way are mixed with salt water and reaching the reef lagoon can return to the surface through the water eyes.

of the 2,297 $m^3$ delived daily only 1,209 $m^3$ were treated; this means thant only 47.3% were poured directly to the aquifer. In fact, the study of Rico (2014) was found a positive relationship between the increase in the population of Puerto Morelos and the amount of δ15 N between 1970 and 2010 (Figure 39). The study used coral cores (Figure 40) and determined the date by sclerochronology.[4] In addition, there is the pressure of a floating population due to tourism. In 2012, in Puerto Morelos an average occupancy of 72.5% was registered equivalent to 5,516 tourists, representing an increase of 40% compared to the resident population.

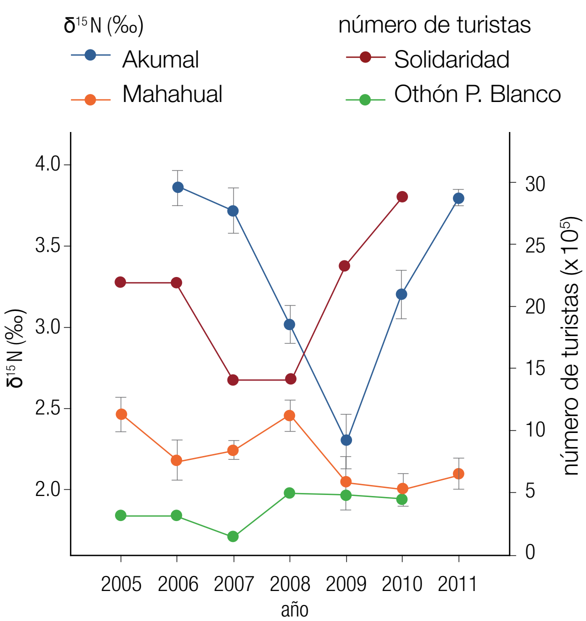



**Figure 37.** Number of nitrogen (Isotope 15) in part per thousand (n = 5) number of tourists between 2005 and 2011 in Akumal and Mahahual, the bars represent standard errors (taken from Baker et al. 2013).

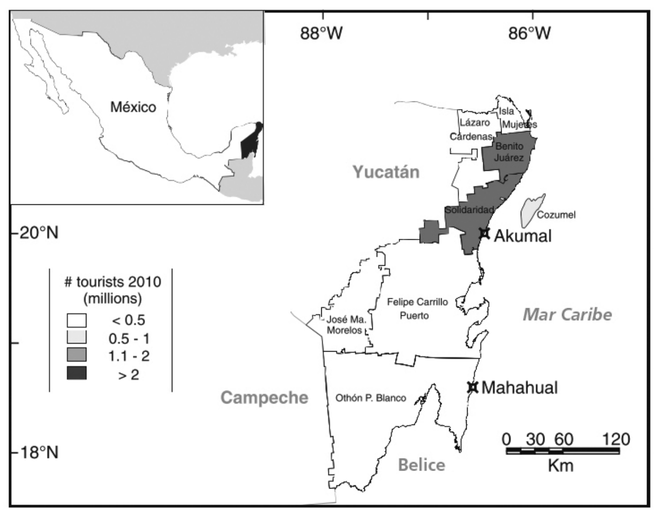



**Figure 38.** Location and tourism demand in 2010 Mahahual and Akumal (taken from Baker et al. 2013).

## Conclusion

Puerto Morelos studies show that wastewater can contaminate the fresh water lens and coastal environments (beaches, cenotes, mangroves, etc.). This assumption is supported with the highest concentration of anthropogenic nitrogen and the presence of coliforms in these environments. In addition, a correlation between the number of tourists and the amount of nutrients in the reef was found.

[4] Coral growth can be determined by the extent and rate of calcification. During the months of higher temperatures (July-August) usually produce a high density band because of a higher rate of growth, therefore the presence of the band can be used to estimate the age of the fragment. In this case was used the organic matrix of the coral which is formed by stable proteins that can remain intact for hundreds of years. It also includes proteins synthesized during biomineralization process, contributions of matter by endolithic algae, bacteria and incorporation of particulate material present in the water column.

Cuadro 4. **Average occupation and floating population in Puerto Morelos (2008-2012)**

| *Year* | *Nomber of rooms* | *Average occupancy* | *Floating population* |
|---|---|---|---|
| 2008 | 2 585 | 61.6 | 2 389 |
| 2009 | 5 036 | 53.8 | 4 064 |
| 2010 | 5 072 | 73.2 | 5 569 |
| 2011 | 5 072 | 74.3 | 5 653 |
| 2012 | 5 072 | 72.5 | 5 516 |

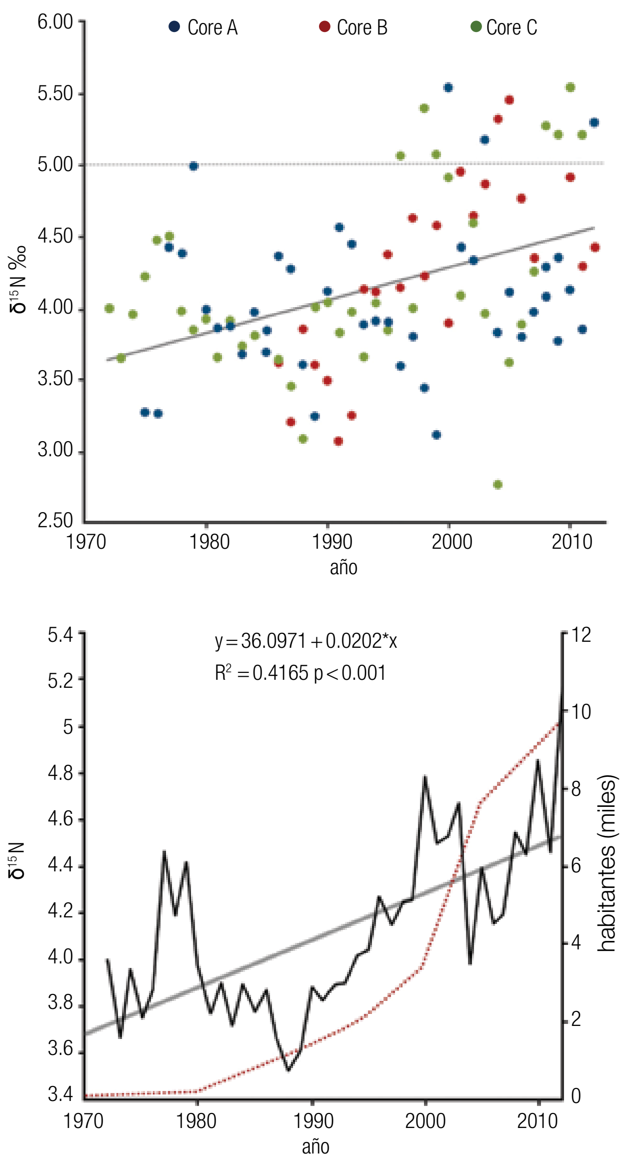



**Figure 39.** Above, temporal evolution of 15N in the organic matrix of the 3 cores extracted from *O. faveolata*; the dotted line indicates the higher values of 5 ‰. Below, correlation between the average annual values δ 15 N [solid line] and data from population growth in Puerto Morelos from 1970 to 2010 [dotted line] (taken from Rico 2014).

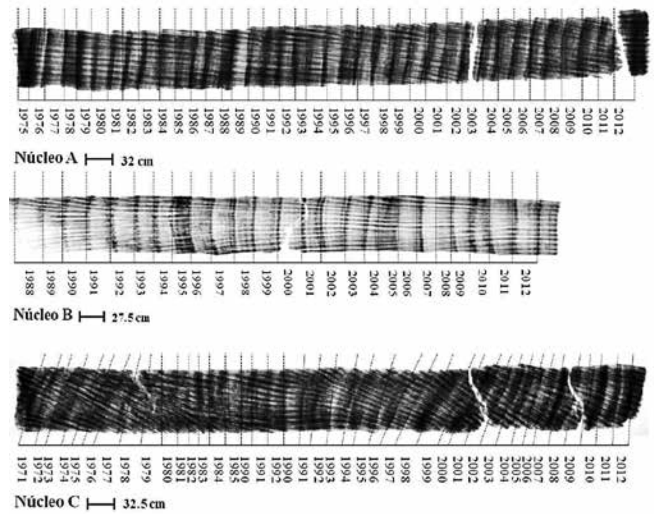



**Figure 40.** Positive of the RX plates and dated annual by density bands, from the job by Rico 2014.

### 1.5.4 **There is a correlation between the concentration of nutrients and the presence of diseases in corals**

What are the consequences of this nutrient discharge in the health of corals and the reef? In a study in Saint Croix (Virgin Islands, US) two ecologically and geologically comparable sites were compared, but with different exposure to sewage. The study shows that the site exposed to wastewater has a disease prevalence of 13.6% in 7 of the 10 species studied which is significantly higher than the prevalence of 3.7% on the site free of wastewater (Kaczmarsky, Druad, and Williams 2005). Also in the Island of Guam it was found a significant relationship between the severity of the disease of the yellow band and δ15 N levels (Redding et al. 2013). It is generally known that the reefs of Yucatan have high levels of diseases which are likely to change richness and roughness. The loss of species could even reach higher trophic levels (Ward et al. 2006).

A controlled study conducted in Puerto Morelos showed that a moderate increase in nutrients can substantially increase the severity of disease (Figure 41 and Figure 42) (Bruno et al. 2003). The authors propose that the pathogens involved in the experiment (*A. sydowii* and *Vibro* spp.), use the additional nutrients to increase their fitness and virulence. Based on this, Baker et al. 2010 suggest that fact that the incidence of yellow band disease in Akumal is double than in Mahahual is due to sewage pollution.

Monitoring of 12 years (1993-2005) carried out by Rodríguez-Martínez et al. (2010) shows an increase in the amount of disease present in Puerto Morelos (Table 4). The authors attribute this to the increase in temperature, however, it could be a synergistic effect with contaminants. The temperature reduces the resistance of coral and pollution increases the virulence of the disease (Rodríguez-Martínez et al. 2010; Bruno et al. 2003). The continuing incidence of these diseases can result in a total loss of coral (Redding et al. 2013).

Reef-building corals are excellent competitors in low-nutrient environment, they can recycle nutrients between host and zooxanthellae and are efficient in photosynthesis (Fabricius 2005). However, as we saw, these conditions are changing rapidly due to human activity in the coastal zone. The new conditions may favor their competitors, mainly to macroalgae (Jackson et al. 2014) due to the increased presence of nitrogen. It has been found that an increase of 50% nutrients can cause a loss of coral coverage of 50% (Loya 2004). The form of competition is relatively passive. Macroalgae occupy space coral after their death, preventing the establishment of new colonies of coral (Fabricius 2005) and prevents their recovery. For example, in Puerto Morelos Hurricane Gilbert caused great loss of coral (over 50% coverage) on the reef, which has not been recovered, and until 2005 only it had one coral coverage of 3%. However, macroalgae coverage was 41.5%, demonstrating a better adaptation to the new conditions (Rodríguez-Martínez et al. 2010).

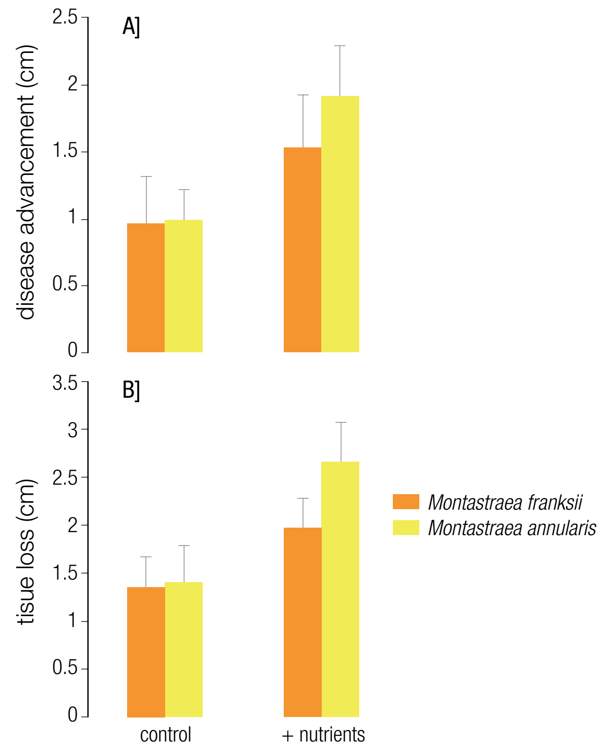



**Figure 42.** Resultados del experimento (*in situ*) de enriquecimiento de nutrientes con A] la enfermedad de la banda amarilla (yellow band disease) y B] pérdida de tejido de coral *Montastraea franksii* y *Montastraea annularis* durante 90 días. Las barras representan la media +/- DE (n = 10), (tomado de Bruno et al., 2003).

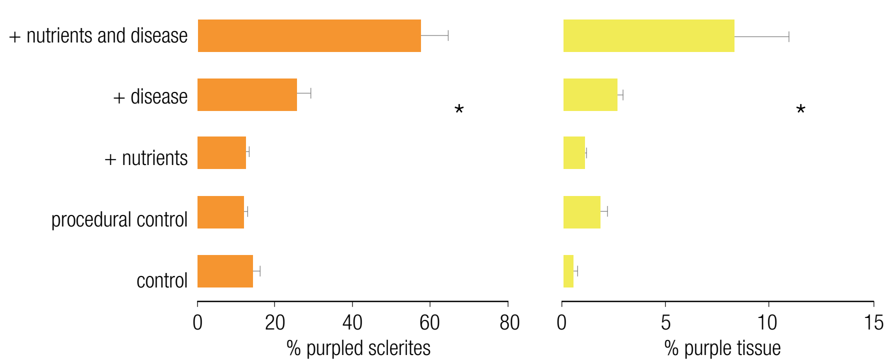



**Figure 41.** Effect of five treatments on the percentage of sclerites and purpled tissue (two ways to measure the severity of aspergillosis). The bars represent the mean +/- SD (n = 10); asterisks represent significant differences ($p < 0.05$, Tukey-Kramer test) compared to other treatments (taken from Bruno et al. 2003).

Table 5. Socio-demographic parameters and major events in Puerto Morelos, between 1993 and 2005. Black band (BB), dark spot disease (DS), white band (WB), Acroporas´ Serriatosis (WPx), and yellow band (YB) (Rodriguez-Martínez et al. 2010)

| *Year* | *Population* | *No. rooms* | *Hurricanes* | *Bleaching* | *Diseases* |
|---|---|---|---|---|---|
| 1993 | - | - | - | 0 | nd |
| 1994 | - | - | | 0 | nd |
| 1995 | 2224 | 401 | Roxane (3) | Severe | nd |
| 1996 | - | - | | 0 | nd |
| 1997 | - | - | | Low | |
| 1998 | - | - | | Moderate | WB, WPx |
| 1999 | - | - | | 0 | nd |
| 2000 | 3438 | 401 | | 0 | DS, WB, WP, WPx, YB |
| 2001 | - | - | | 0 | BB, DS, WB, WP, WPx, YB |
| 2002 | - | - | | Low | nd |
| 2003 | - | - | Ivan (5) | Moderate | BB, DS, WB, WP, WPx, YB |
| 2004 | - | - | Emily (2) | Moderate | BB, DS, WB, WP, WPx, YB |
| 2005 | 7726 | 1455 | wilma (5) | Severe | BB, DS, WB, WP, WPx, YB |

Bruno et al. 2003 Methodology

The experiments were made in situ at a depth of 8 to 10 m for 90 days, beginning on June 19.

Aspergillosis experiment. Five treatments were used: i] control without handling, ii] control manipulation, iii] experimental infection, iv] nutrient enrichment and v] experimental infection + nutrient enrichment. Healthy colonies were inoculated with inserts of diseased neighboring colonies. The severity of disease was measured by the percentage of sclerites and infected tissue.

Yellow band experiment. Two species *M. annularis* and *M. franksii* were used. All colonies showed signs of disease. Two factors were evaluated for the treatment (effect and control) and species (*M. annularis* and *M. franksii*). The effect of the disease was measured through disease progression. Nutrients were manipulated by disseminator nylon bags.

## Conclusión

Studies in the Caribbean and Puerto Morelos have confirmed that there is a correlation between increased concentration of nutrients and the increased presence of disease in corals. The diseases cause mortality and decrease the resilience of corals. The space is occupied by macroalgae that increase their growth due to the presence of nutrients. These conditions cause reef degradation and loss of reef structure and complexity.

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Mayan coast 2014. Photo: Fernando Secaira/TNC.

# 2. DUNES PROTECT BEACHES AND THE COASTAL ZONE

The coastal system is under continuous stress, about 41% of the world's population lives within the strip of 60km of the coastline (Martinez et al. 2007) and it is expected that by 2020 it will raise to 60% (Lithgow et al. 2013). Besides, today 21 of the 33 megacities (over 20 million of population) are in the strip of 100 km (Martinez et al. 2007). Human activities have transformed about 30% of the area inside that strip (Martinez et al. 2007). These can be classified into: i] residential and recreational; ii] industry and trade; iii] sewage disposal; iv] agriculture; v] mining and vi] military activities (Lithgow et al. 2007). These, together with climate change, will continue to increase the pressure on the coastal zone. So it is clear that the risks for infrastructure will be greater with increasing erosion and sea level (Feagin et al. 2015).

Mexico had 800,000 ha of coastal dunes, which were distributed in 80% of the coastline. About 50% of coastal dunes have been transformed for agricultural use or urbanized (Jimenez-Orocio et al. 2014). Between 1970 and 2000 9.3% of the natural vegetation was lost in coastal municipalities

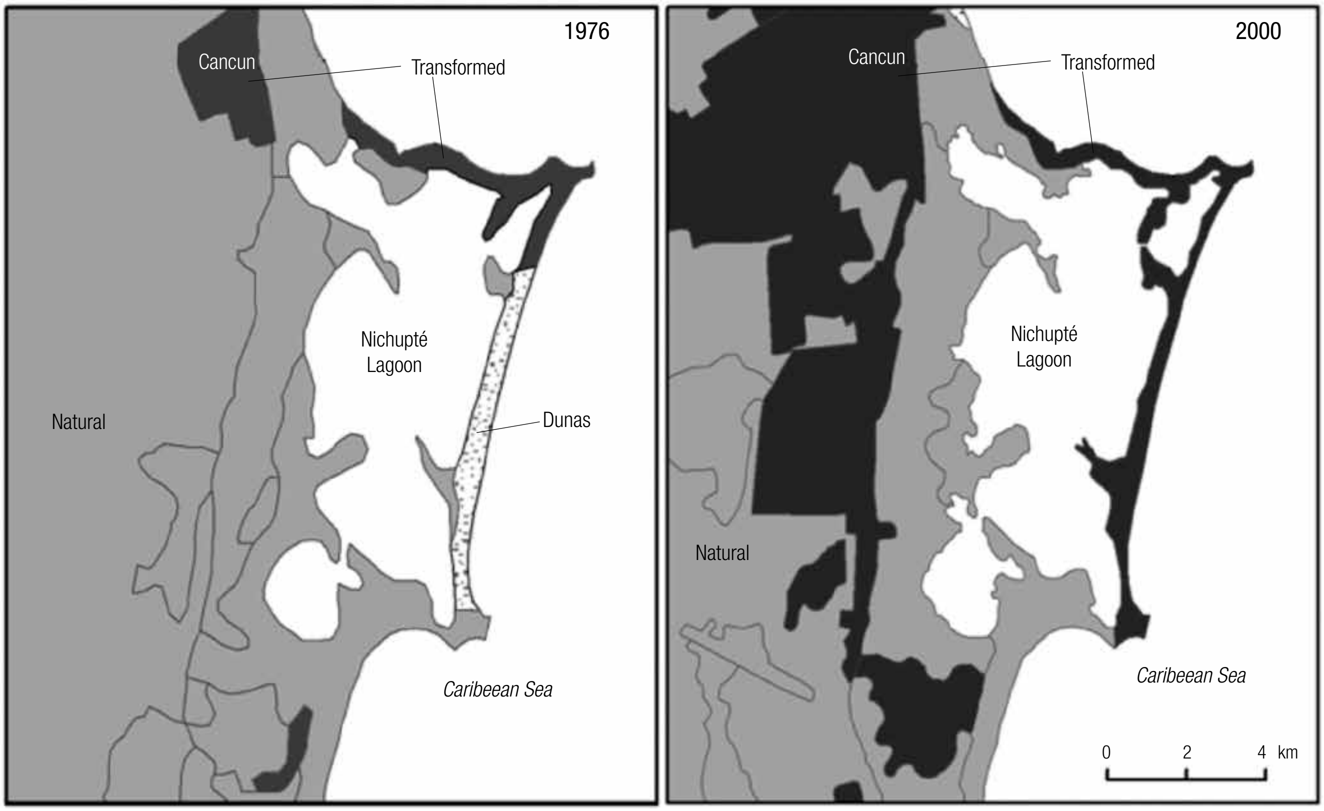


**Figure 43.** Example of loss of coastal dune vegetation by tourism developments in Cancun, Quintana Roo (taken from Seingier et al. 2009).

and 14% of coastal dunes. There are alarming cases like Cabo Falso, the Southern end of the Baja California Peninsula, where 45% of the vegetation cover was lost due to the activities of all-terrain vehicles. The loss of vegetation has changed wind circulation and erosion patterns, increasing the sedimentary instability of the system (Camacho-Valdez et al. 2008). The Caribbean is the region with the greatest loss of dune vegetation; the transformed area of coastal municipalities in the Yucatan Peninsula increased from 4,119 $km^2$ in 1976 to 11,198 $km^2$ in 2000 (an increase of 172%, the largest in the country).

Despite the large investment and the economic exploitation of the coastal zone, there is a delay of information and research of coastal dunes. Mainly in the evaluation of environmental services, such as protection and stabilization of beaches. Only 1% of the dune literature developed in the country deals with the evaluation of these ecosystems. In addition, the studies of Quintana Roo, are very few [Figure 44] (Jimenez-Orocio, et al. 2014).

### 2.1 The coastal dune vegetation consolidates the soil through the roots; trapping and holding the sand through leaves and branches. Therefore, vegetation removal and deterioration exposes the sediment and facilitates the removal by wind and waves

The vegetation is necessary for the formation and consolidation of the dune. There are five factors that determine the formation of dunes: the contribution of sediment, wind speed, grain size, cohesion between particles and the presence of obstacles (Martínez et al. 2014). The vegetation consolidates the dunes because:

- Constitutes obstacles to the wind, slowing it down and facilitating the deposition of grains.
- Reduces erosion by protecting the substrate surface with their stems, leafs and roots
- Increases the cohesion of the particles by providing organic matter and maintaining moisture.

When the wind has a higher speed than ~4.5 m/s sand grains are raised and jumps near the surface of the beach, mov-


**Figure 44.** Geographical distribution of research on coastal dunes of Mexico (taken from Jimenez-Orocio 2014).

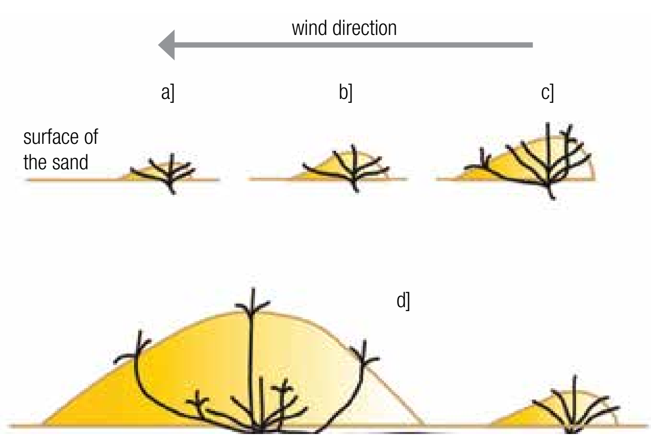


**Figure 45.** Formation of dunes. It starts with a small structure, generated by the accumulation of sand around vegetation or another obstacle [a, b]. In the case of vegetation, it can continue to grow as the mound increases in size, which gives stability to the dune [c, d] (taken from Martinez et al. 2014).

ing in a phenomenon known as saltation. As blowing grains bounce on the surface they trigger more grains to come into motion. When an obstacle such as vegetation is present, the wind is decelerated as instead of because it is forced to change direction to surround the object, causing the grains to fall and form mounds. These mounds gradually envelop the obstacle making it bigger, which obstructs more wind (Figure 45) (Martinez et al. 2014, Pye and Tsoar 2009).

The vegetation consolidates the dunes as roots, stems and leaves protect the surface from the wind. The shape of the vegetation and physiology are important, for example, pastures are usually good accumulators of sediment because given their flexibility they can form a carpet during a storm; their nodes can develop roots stems and roots despite being covered by sand. As the topography is gaining altitude, interactions between plants become increasingly complex resulting in a larger number of communities. Without vegetation, the only forces that maintain the profile of the dunes are gravity and intragranular friction (Feagin et al. 2015)

Vegetation increases the cohesion of the substrate particles. Vegetation provides matter to sediment composition (Figure 46), which increases the cohesion between particles. Besides, vegetation prevents desiccation of the sediment while the soil remains moist, its intermolecular cohesion is greater (Feagin et al. 2015).

The effects of a storm over the dune depend on the type of impact it has (Figure 47). According to Sallenger Jr., (2000) 4 levels of impact can be distinguished: i] Swash: when the water level is limited to the front of the beach, without reaching the dune; in this case the beach is eroded but recovers without

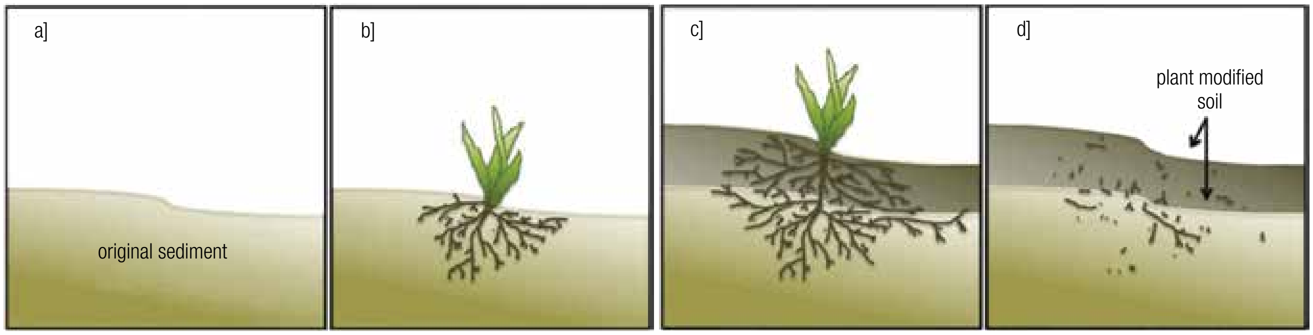


Figure 46. Vegetation alters the physical structure of the sediment through their roots and modifies the same properties of the sediment. a] In the case of sediment, the only forces that keep it stable are gravity and intragranular friction; b] when the vegetation grows it stabilizes the sediment through their roots; c] at a later stage, the vegetation modifies sediment composition increasing its stability; d] even when the vegetation disappears, is a residual stability due to the change in composition made by vegetation (taken from Feagin et al. 2015).

Silva et al 2016 Methodology

The experiment was carried in the channel wave (width: 0.8, high: 1.2, length: 37 m) of Instituto de Ingeniería of UNAM (II-UNAM) Figure 48. Which is equipped with a wave generator from a piston as well as an absorption dynamic system. The channel is divided into two with an acrylic wall of 1 cm in the last 8 m of length (from 21 to 29.1 m), in order to evaluate two profiles at once. A profile "A" taken as a reference, is similar to the one used in a previous study by Kobayashi et al. 2009, it is representing a narrow dune with berm. Profile B, is a scale model of the typical profile found in the coast of the Gulf of Mexico, where plants and sand were taken. 11 sensors were used for ultrasonic waves and 6 speed profilers distributed in both profiles according to Figure 48. In the experiment a total of 24 conditions were tested, including 2 profiles with and without berm, 3 in storm conditions and 4 vegetation densities (without vegetation and with low, medium and high density) (R. Silva et al. 2016).

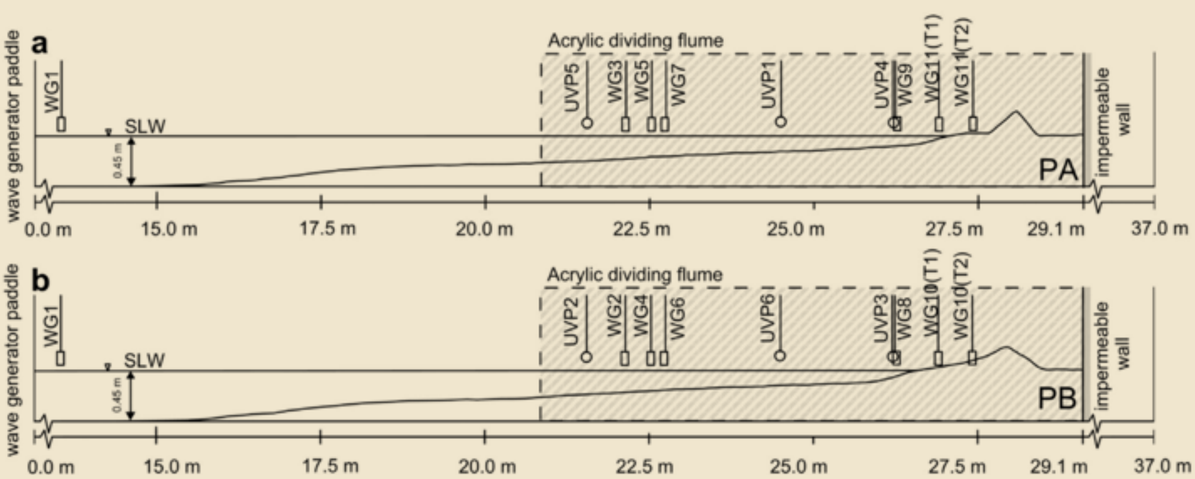


Figure 48. Profiles used in the experiment of Silva et al. 2016: UVP = profilers supersonic speed and WG = sensors to measure the waves; profile A similar to that used in the study of Kobayashi et al. 2009, and profile B scale model of the typical profile found on the shores of the Gulf of Mexico (taken from Silva et al. 2016).

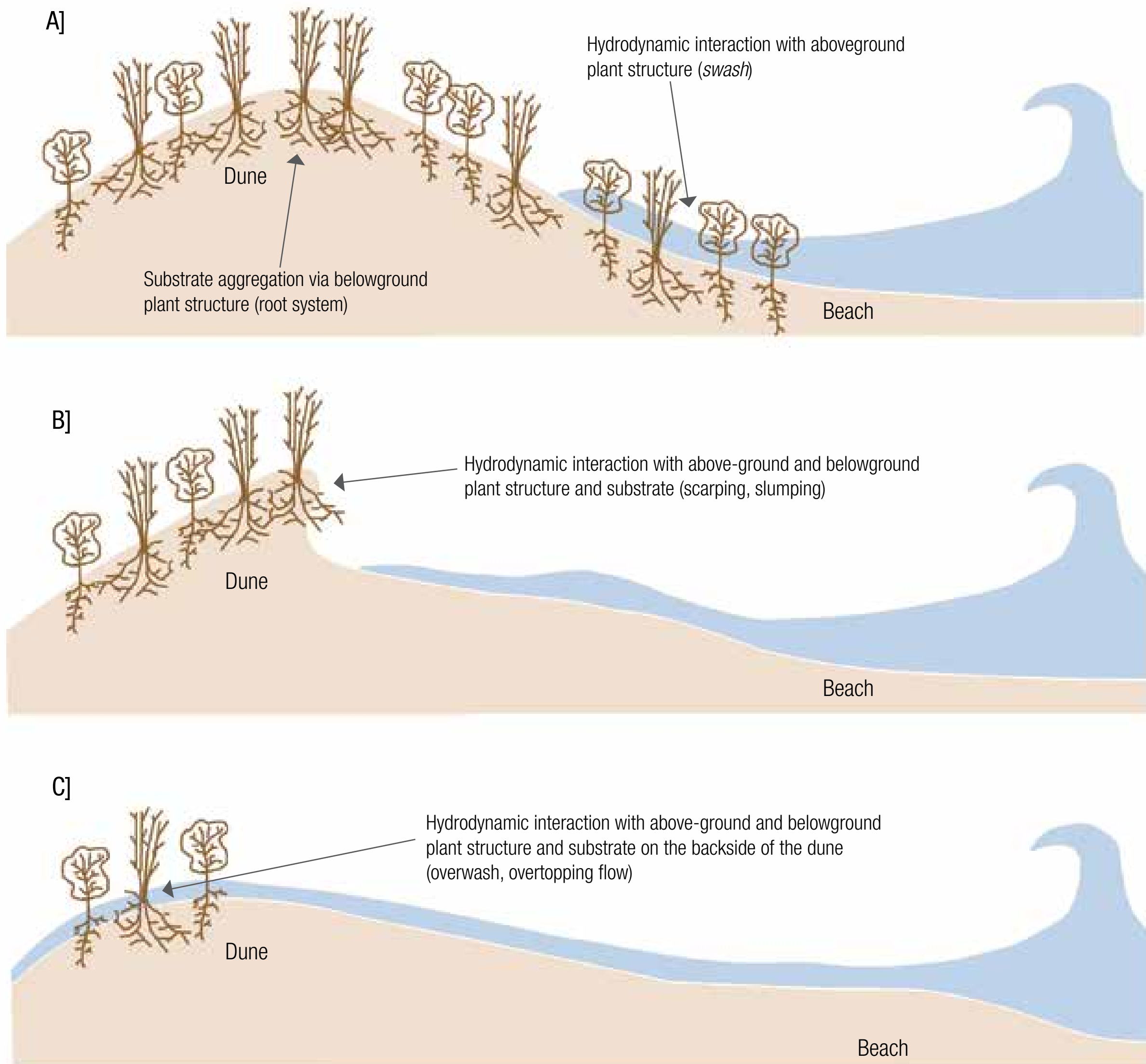


**Figure 47.** Surface and internal interaction of plants, substrate and waves. A] First level of impact swash; B] Escarpment of dunes during the regime of collision; (c) overwash and flooding dune. During (a) and (b) the flow is bidirectional while for C] is unidirectional (taken from Feagin et al. 2015).

producing a net loss of sediment; ii] Collision: when the water level reaches the front of the dune, dragging sediment into the sea and in the current parallel to the coast; iii] Overwash: when the tide level reaches the height of the dune; iv] Flood: when the whole dune is submerged (Sallenger 2000; Silva et al 2016).

Each one of the impact levels will interact differently with the dune. In the three strongest levels, stems and leaves (surface component) and roots (sub-surface component) reduce wave energy. This has been verified by laboratory measurements in the wave flume of the Engineering Institute of UNAM (Silva et al. 2016). The surface vegetation components create friction and mitigate the waves and even reduce the level of flooding. The roots fix and stabilize the sediment, increase their resistance and reduce wave energy by increasing the effort required to move the grains. The study of Silva et al. (2016) found that the profile shape has a great influence and must be considered in the analysis. However, there is a lack of studies to distinguish between surface energy and internal dissipated energy by the vegetation (Silva et al. 2016).

In Mexico there are successful cases where replanting vegetation has allowed the recovery and stabilization of the coastal dune. For example, when the Port of Veracruz was expanded in 1996 the dune was completely flattned and vegetation was totally removed. A modified and unstable dune, 2 km long and 10 to 20 m high, was left parallel to the coastline. This dune turned out to have great mobility and during the season of "Norths" it was moved inland to the nearby neighborhoods (Moreno-Casasola et al. 2008). It was necessary to restore dune stability by replanting vegetation. Three plant communities whose specimens could be obtained in sufficient quantities were used. The communities were 1] a cactus grown in dunes *Opuntia stricta*; 2] tall grass *Panicum maximum* and 3] short grass *Panicum* and *Paspalum lividum langei*. The three types of communities managed to stabilize the dune and restored the environmental protection service, at least during the 5 years of the experiment. It is expected that the community formed by cactuses gradually recover the original vegetation because it leaves more space available and facilitates the development of other species. By contrast, pasture communities tend to colonize almost completely the dune and do not allow the colonization of native species. Therefore, it is important to define the ultimate goal of re-colonization (native vegetation or mono-farming) to properly select species (Moreno-Casasola et al. 2008).

## Conclusion

The vegetation is important for dune formation, as well as for stability. The contribution of the vegetation is multifactorial as it provides the following services: i] short-term stabilizer of the dune by their roots; ii] stabilize the dune long term, changing the composition and properties of the sediment and iii] mitigating the effect of storm surge and flooding friction and turbulence. It can restore the stability of a dune by planting vegetation and regain its coastal protection function for which there are successful cases in Mexico (Veracruz).

## 2.2 **The dune works as a sand reserve which allow compensate the beach erosion in storm events**

The way the dune responds depends on the size of the storm. In the event of a collision, large amounts of sediment are taken from the dune and redistributed along the beach profile as in Puerto Morelos during Hurricane Wilma in 2005 (Figure 49). Dry beach increased by 30 meters, in contrast to Cancun beaches were completely eroded. According to the analysis (Mariño-Tapia et al. 2014; Silva et al. 2014) three factors led to this increase: i] the protective function of coral reef; ii] the sediment brought to Puerto Morelos from the beaches of Cancun and iii] the distribution in the beach of the sediment provided by the dune. It was noted


**Figure 49.** Effects of Hurricane Wilma in Puerto Morelos. Left, before and right after the hurricane. The beach was an accretion of almost 30 m across the coastline, also a large swath of vegetation was lost. One of the explanations, besides the sediment from Cancun, is that the last dune covered by vegetation was eroded and its sediment was redeployed on the beach profile (Mariño et al. 2014) (taken from Silva et al. 2014).

before that Playa Delfines, a public beach with dunes, presented the least erosion in Cancun (Silva et al. 2006).

The most interesting is the level of resilience. After six months, the coastline and the beach of Puerto Morelos returned to its original condition while in Cancun the authorities had to make a filling of beaches (Silva et al. 2014, Silva et al. 2006). That is, Puerto Morelos in a relatively natural state retains its ability to recover, while Cancun in its current conditions lacks resilience (Silva et al. 2014, Diez et al. 2009).

### 2.3 **Dune represents a natural protection against storm surges reducing flooding in inland areas behind the dune**

The height of the dunes are proportional to the prevailing height and wave energy. Cancun dunes used to have a height of 12 meters (Silva et al. 2006) and Puerto Morelos dunes were 3-4 meters high. As it was explained, the dune structure and vegetation reduce wave energy and surge height acting as natural dikes that prevent inland flooding caused by storms surges. Even if the surge and wave overwash the dune the resulting flooding would be far less due to the reduced wave energy and reduce water volumen that can overtop the dune. Therefore there is increasing interest in the use of natural solutions for coastal protection known as bioshields.

## Conclusion

Currently, there is increased interest in the implementation of natural solutions to coastal management, particularly the use of bioshields. For example, dunes with preserved vegetation for protection in extreme weather events (Feagin et al. 2015). Rigid methods as dikes and breakwaters alter the dynamics of sediment transport affecting ecosystem functions. Also in such a dynamic system as the coast, mechanisms are needed which can adapt to the changes that will accelerate, thanks to climate change. We have already seen how the vegetated dune may stabilize and protect the sediment before and during the storm. Another great quality is that after the storm, vegetation also helps natural recovery. There are plants that may scatter from the pieces that are torn during storm (*U. paniculata*) as well as seeds adapted to be carried by the current (*Cakile lanceolata*) (Feagin et al. 2015). So these structures provide protection short- and long-term (resilience). Besides, the implementation and maintenance costs are lower (Feagin et al. 2015). However, there is still a lack of important information, not only regionally, but also internationally (Feagin et al. 2015; Silva et al. 2016; Martinez et al. 2007).

### 2.4 The storm drains allow the inland wetlands set off to the sea and vice versa, allowing a release of energy, preventing further damage to the dune and to the present infrastructure

Storm surges increase their height and pressure causing erosion along the barrier island when they cannot release their energy through storm drains. Numerical experiments by Silva et al. (2012), suggest that openings on the barrier reef could be a very important process during storm events. Before development of tourism this events could open drains concentrating on them the effect of storm surge. The concentration of the effect in the mouth decreases the pressure in the rest of the island barrier which reduces the erosive effect. Today the tourism infrastructure built on the coast has closed those drains, making it more rigid to the system.

#### 2.4.1 The natural replacement of the water of the lagoon

Another function derived from opening storm drains, is the water exchange in the lagoon system. This system has presented several cases of eutrophication because their connection to the sea was limited by the changes made by the hotel infrastructure (Guido Aldana et al. 2009). Silva et al. (2012) model shows that the entire lagoon system interacts with each other (Buenaventura lagoon; Nichupté Lagoon and Bojorquez Lagoon) and sea during storm surges. This interaction allows the exchange of the water of the entire system and prevents eutrophication (Silva et al. 2012).

## Conclusion

The natural opening of mouths during storm events is a mechanism that helps release energy and concentrates on certain parts of the beach (in this case the barrier island), which mitigates erosion in other areas. It also helps the natural replacement of water in the lagoon system, reducing eutrophication events.


Figure 50. a] Punta Cancun in the 70's before the tourism development: The natural storm drains can be appreciated exposed during storm events. b] The current tourism infrastructure have modified and blocked storm drains (taken from Silva et al. 2012)

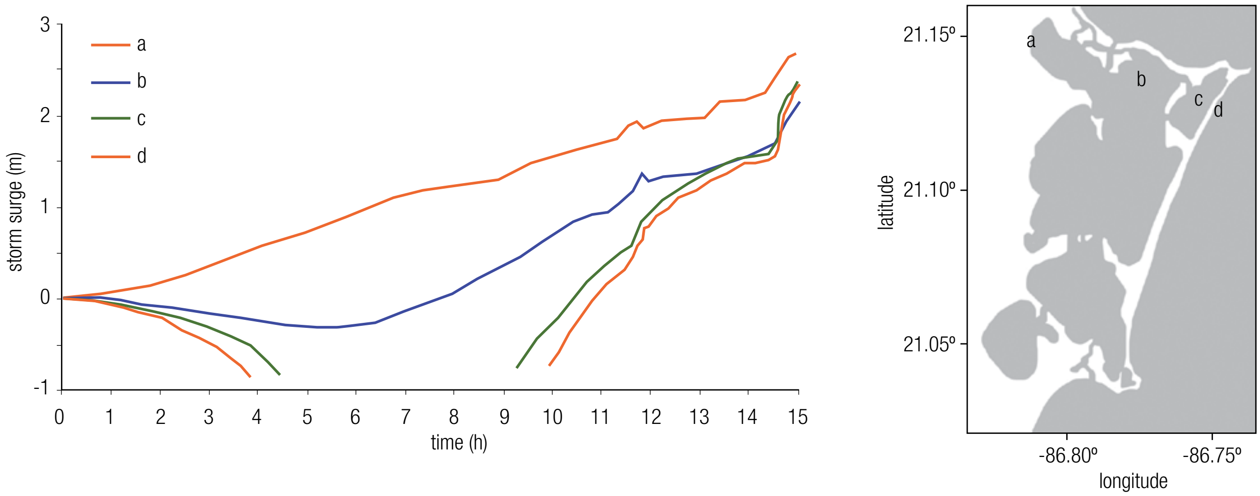


**Figure 51.** Storm surge model during Hurricane Wilma (taken from Silva et al. 2012.) a] Buenaventura lagoon; b] Nichupté Lagoon; c] Bojorquez lagoon; d] beach area. During the storm water bodies are emptied and filled completely, in fact there is a point about 14 hours where practically all bodies are united by the storm surge, creating a water exchange.

### Silva et al. 2012 Methodology

The analysis consisted in the implementation of a wind and wave model between 1948 and 2007 using the hybrid model WAM-HURAC, itself composed by the parametric model HURAC and wave generator of third generation WAM. The tool enables a continuous record of waves and larger scale events (hurricanes and storms). It allows evaluation of the typical surf zone (address and Hs) and the comparison of magnitude of large-scale events. The model was tested and validated with records of 7 buoys in the Gulf of Mexico and the Caribbean. Then MATO and WAPO programs were used to reproduce the storm surge and waves developed in the Cancun area during Hurricane Wilma. It used *in situ* measures of an acoustic current meter Doppler (AWAC) during the hurricane. Finally, videos and aerial and satellite photographs of the area collected over several years by the II-UNAM were used.

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