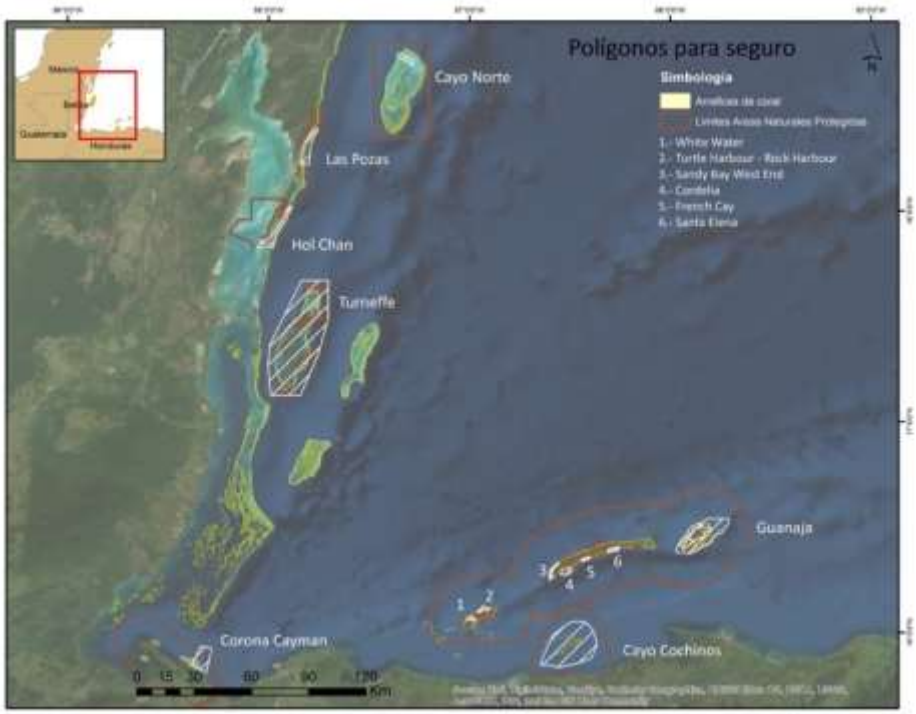
PROPOSAL OF A PARAMETRIC INSURANCE IN THE MESOAMERICAN REEF



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1 Importance of insurance against hurricanes for reefs

Hurricanes have a destructive effect on reefs, which is supported by an established body of research (Beeden, et al., 2015; Gardner et al., 2005; Alvarez-Filip et al., 2011). It is estimated that a category 3-5 hurricane in the Caribbean can cause the loss of 10-60% of live coral cover. The loss can be catastrophic and much higher than the annual loss of live coral cover caused by all the other factors combined (water pollution, bleaching, diseases, etc.) of 2.2%. The annualized loss of a site impacted by hurricane increases from 2.2% to 6.7% (Gardner et al 2005). In other words, the annual loss would triple. It is widely accepted that post storm repairs facilitate a stronger recovery of the reef.

Repairing damages after a storm are costly, as it requires the mobilization of specialized and well-trained divers to collect debris, re-attach coral fragments, stabilize coral colonies, and establish nurseries to allow smaller fragments to grow and eventually relocate in the reef. Cost ranges from USD 100,000 to USD 300,000 for a site of 20 km long, depending on the extent of the damage and the scope of the response.

Reef managers need different sources of funding to implement a post-storm response. An insurance is an appropriate instrument to transfer the financial risk when strong storms affect the area. Therefore, The Nature Conservancy (TNC) and Reef Rescue Initiative, managed by MARFund and funded by the German Government via KfW, envisioned the development of an insurance for reef against hurricanes in the Mesoamerican Reef. TNC, in collaboration with several universities and the Quintana Roo Government in Mexico, developed a first concept for the Mexican Caribbean in 2018. The QR Government, in turn, requested quotes from insurance companies and purchased a policy via the Coastal Zone Management Trust in 2019.

In order to develop an insurance concept for the MAR, MARFund, TNC and partners first gathered and generated information essential to design an insurance:

1. Identification of sites to be insured: CONANP in Mexico, Fisheries Department in Belize, CONAP/MARN in Guatemala and HRI-Honduras, in consultation with local stakeholders, identified the priority sites that required funding to conduct a post storm response. The selection process was led by MARFund, with TNC support. National agencies and key stakeholders held meetings in each country to assess proposed site in each country using criteria such as biodiversity value, environmental services provided, extent of threats and eventual stakeholders´ capacity to respond and to finance the insurance.
2. Assess the cost of repair and restoration. First, TNC and partners developed a protocol that outlines the post storm activities (Zepeda, et al., 2019), detailing the techniques, the activities, equipment and materials needed and human resources. Based on this detailed account, MARFund hired a consultant to estimate the cost of implementing those activities in several sites across the MAR countries (Whiterock et al., 2019).
3. Correlation of damages to reef caused by hurricanes, with the characteristics of reefs and hurricanes. An analysis, conducted in collaboration of MARFund, UNAM-ICMYL and TNC, estimated the damages caused by hurricanes to live coral cover and rugosity, and assess if there were statistical correlations between the reef characteristics with hurricane characteristic and damages to reefs (Perez et al., 2019). The analysis identified that maximum wind speed, wind-speed at impact, live coral cover prior to the storm and wind-ward location are the four main characteristics correlated with damages to reefs. The analysis encompassed 343 sites throughout 24 countries in the Caribbean basin with data from 1973 to 2017 (44 years).

The process to design the insurance concept followed these steps:

4. Estimation of the area of reefs with live coral cover within the selected sites.
5. Estimation of funding needed to implement a post storm response in each site.

6. Selection of the values of the parameter (wind-speed at impact and maximum wind speed) to trigger the insurance, for each site or aggregation of sites.
7. Develop of several scenarios of policies, combined the following factors;
    a. The extent of the polygons.
    b. The parameter and the value to trigger the insurance.
    c. The values of the payout
    d. The mutualization of risk among the 7 sites
    e. The responsibility limits.
8. Identification of the criteria to assess the benefits and disadvantages of the different scenarios to allow the potential buyer to choose the most appropriate concept.

2 Summary of key aspects of the analysis

The analysis considered the following key aspects:

1. We calculated two scenarios to estimate the cost of repair to then decide on the payout needed for the insurance.
    a. One scenario calculates the cost to restore the entire projected area damaged
    b. The other scenario estimates the cost of deploying the soon-to-be response capacity, considering 3 brigades in each country.
2. We considered several scenarios of polygons for the parametric insurance. The scenarios considered the following variables:
    a. The extent of the buffer around the reef sites.
    b. The option of clustering the sites.
    c. Distinct polygons for vulnerable reef with higher coral cover.
3. Scenarios are options for stakeholders to compare and to choose the most appropriate which meet their needs. The scenarios will be valued considering:
    a. Cost of the policy
    b. Likelihood of a triggering event
    c. Level of basis risk that shall be hold by the buyer
    d. Appetite of the insurance market to sell such product.

3 Proposed sites to be insured

CONANP in Mexico, Fisheries Department in Belize, CONAP/MARN in Guatemala and HRI-Honduras, in consultation with stakeholders in their countries, proposed the following sites to be insured. All seven sites are located within national protected areas and were selected because they have remarkable biodiversity value and provide important environmental services to the communities around them, such as coastal protection, fisheries and tourism attractions. The Bay Islands Marine National Park proposed a site which is encompassed seven distinct reefs, located apart and in the three islands.

Figure 1: Map of the proposed sites to be insured in the Mesoamerican Reef. The sites with numbers 1 to 6 and Guanaja constitute the site for the Bay Islands Marine National Park.

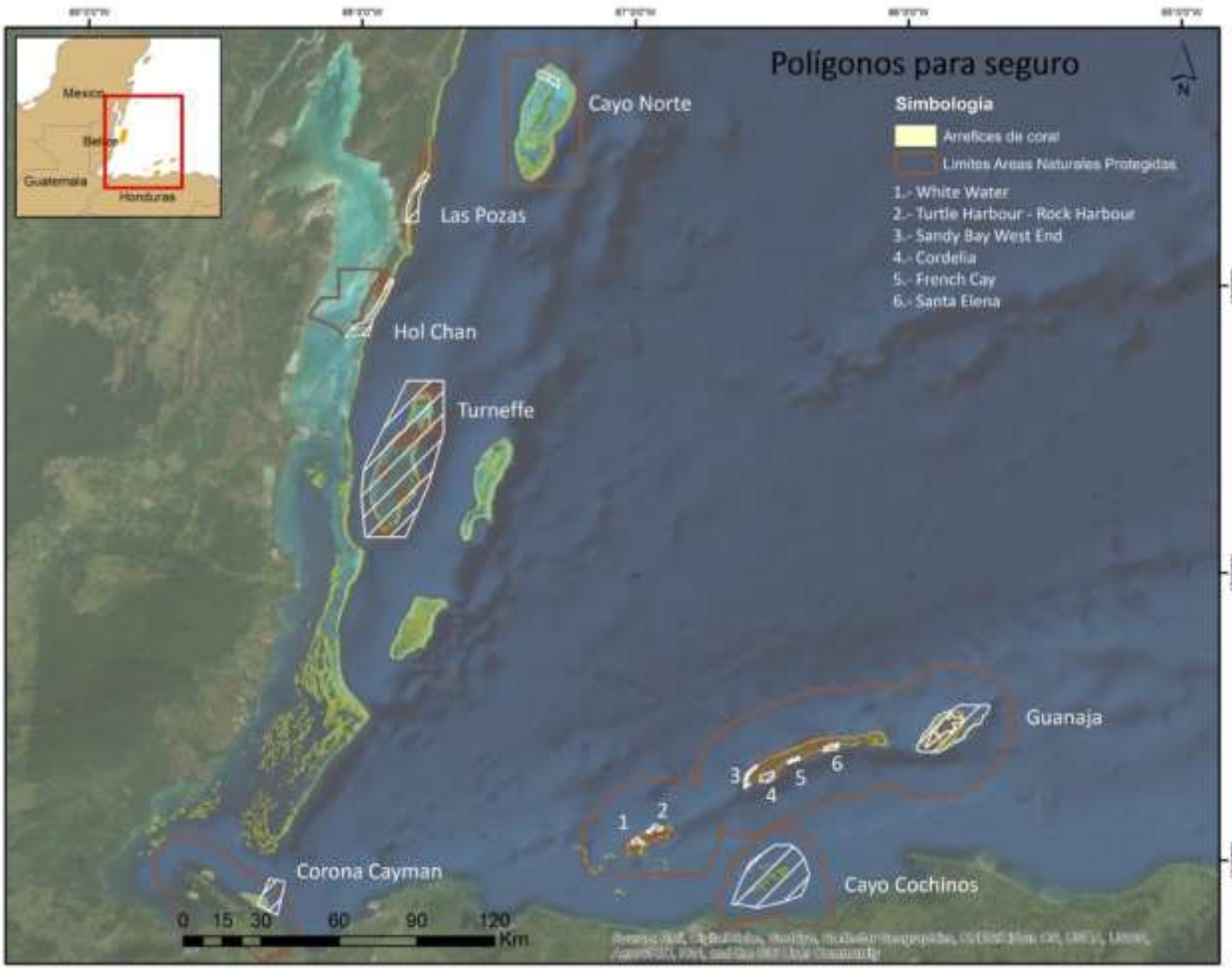


Table 1: Sites to be insured. Site proposed by CONANP, Fisheries Department, CONAP-MARN and ICF, with support from HRI and stakeholders.

Official MPA name	Insured site	Polygon surface (Ha)	Coral surface inside the polygon (ha)*
Mexico			
Banco Chinchorro Biosphere Reserve	Cayo Norte	2,242	163
Xcalak Reef National Park	Las Pozas	7,049	1,785
Belize			
Hol Chan Marine Reserve	Hol Chan	7,074	1,055
Turneffe Atoll Marine Reserve	Turneffe	131,691	7,071
Guatemala			
Punta de Manabique Wildlife Refuge	Corona Cayman	8,605	1,055
Honduras			
Bay Islands National Marine Park		31,766	6,691
	Utila	1,204	402
	1. Turtle Harbour - Rock Harbour	813	314
	2. White Water	391	87
	Roatan	3,819	741
	3. Sandy Bay West End	941	297
	4. Cordelia	1,489	94
	5. French Cay	360	101
	6. Santa Elena	1,028	249
	Guanaja	21,721	4,406
Cayos Cochinos Natural Marine Monument	Cayos Cochinos	49,163	1,447

*Coral cover based on 2013 dataset.

3.1 Live coral cover in each site.

Live coral cover[1] is the characteristic of the reef that is most correlated with damages to the reef caused by hurricane. The higher the live coral cover the more damage the hurricane will cause. High live coral cover means that there are more corals that could be destroyed, which generally still have branched species which are more susceptible to break. Sites with high live coral (above 20%) cover can be damaged by lesser winds, therefore they are far more vulnerable than other reefs with lower coral cover (between 5 to 19%). Moreover, sites with high live coral cover are also the most important reefs for biodiversity, fisheries and tourism.

Given this correlation, we estimated the possible damage that hurricanes may cause (see next section) based on the live coral cover of the proposed site. Live coral cover was obtained from Healthy Reefs Initiative monitoring database (Healthy Reefs, 2019). Each site has several monitoring transects and data and high variability; therefore, we calculated the average value and the upper and lower values for reference. All sites proposed have fair to very good condition, based on HRI´s reef health classification system using live coral cover: very bad (<5%), bad (5-10%), fair (10-20%), good (20-40%) and very good (<40%).

Table 2: Characteristics of proposed sites. Percentage of live coral cover based in HRI dataset (Healthy Reefs, 2019), coral surface based on 2103 dataset and net live coral cover was obtained by multiplying average value by coral surface.

Insured site name	% live coral cover HRI sites			Coral surface	Estimated net live coral cover	Wind direction
	Average	Maximum	Minimum	(ha) Coral cover 2013	(ha)	
Cayo Norte	12.30	27.40	3.30	163	20.06	Windward
Las Pozas	17.70	23.80	11.30	1,785	315.87	Windward
Hol Chan	10.70	16.00	5.20	1,055	112.86	Windward
Turneffe	16.80	35.80	6.30	7,071	1,187.95	Windward
Corona Cayman	44.00	58.50	30.80	1,055	464.12	Windward
Utila	18.85	18.85	18.85	402	75.70	Windward / Leeward
• Turtle Harbour - Rock Harbour	20.60	20.60	20.60	314	64.77	Windward
• White Water	17.10	17.10	17.10	87	14.91	Leeward
Roatan	30.28	36.95	22.38	741	224.37	Windward / Leeward
• Cordelia	41.00	63.30	13.70	94	38.47	Leeward
• French Cay	38.30	38.30	38.30	101	38.69	Leeward
• Sandy Bay West End	24.60	29.00	20.30	297	73.00	Windward
• Santa Elena	17.20	17.20	17.20	249	42.91	Leeward
Guanaja	19.30	40.90	7.30	4,406	850.36	Windward / Leeward
Cayos Cochinos	16.10	29.00	7.80	1,447	232.98	Windward

[1] Coral cover is a measure of the proportion of reef surface covered by live stony corals, which form the reef 's three-dimensional framework. It is indicator most widely used (HRI 2016).

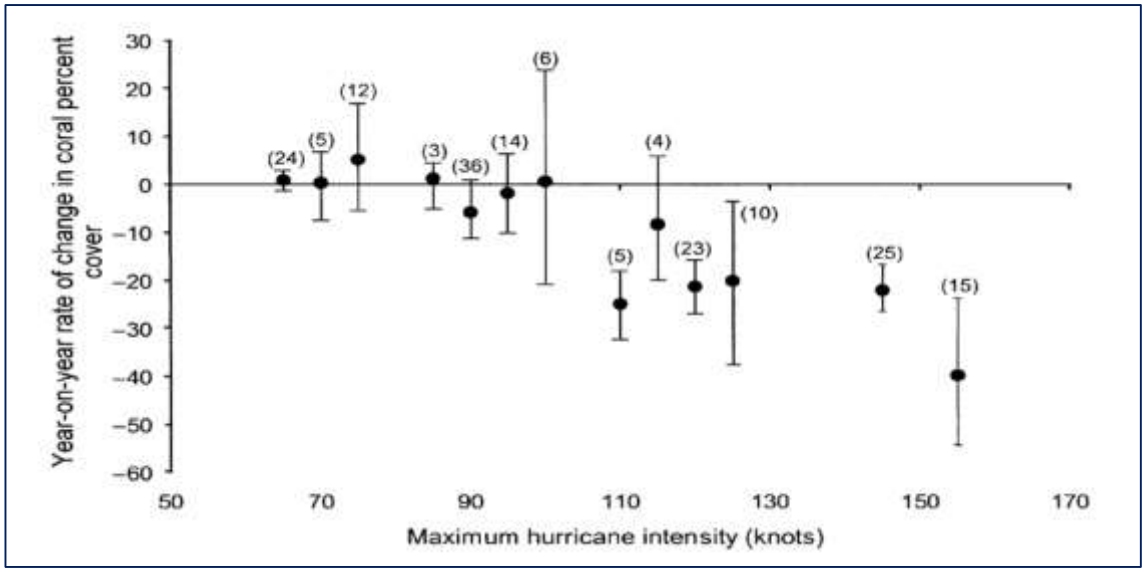
Table 3: HRI monitoring transects in each proposed site used to estimate live coral cover.

Name of the insured site	Name of the proposed site	Monitoring sites
Banco Chinchorro	Cabo Norte	4
Xcalak	Las Pozas	7
Hol Chan	Hol Chan	6
Turneffe	Turneffe	26
Punta de Manabique	Corona Cayman	4
Bay Islands - Utila	Turtle Harbour - Rock Harbour	1
Bay Islands - Utila	Utila	6
Bay Islands - Utila	White Water	1
Bay Islands - Roatan	Cordelia	6
Bay Islands - Roatan	French Cay	1
Bay Islands - Roatan	Sandy Bay West End	6
Bay Islands - Roatan	Santa Elena	1
Bay Islands - Guanaja	Guanaja	16
Cayo Cochinos	Cayo Cochinos	11
Total	Total	96

4 Defining the parameter for the insurance.

An analysis conducted by Gardner et al. (2005) shows a robust correlation between maximum wind speed and damages to live coral cover (see figure 2). This analysis encompassed 200 sites and 20 years for data. The publication does not report any other characteristic of the hurricane, such barometric pressure, storm surge, distance from the reef, etc.

Figure 2: Maximum hurricane intensity or maximum sustained winds are highly correlated with damages to live coral cover in impacted reef (Gardner et al., 2005).



Given the limitations of the previous analysis, MARFund, TNC and UNAM-ICMYL conducted a new analysis to assess a wider range of variables. Pérez et al. (2019) conducted such analysis encompassing 343 sites along the Caribbean Basin with data for the last 44 years. Perez et al. (2019) used a linear mixed model to assess the significance of the principal variables or combination of variables that appeared to be more correlated in the exploratory analysis (see table 4). Only variables with significant sample size were assessed as not all sites have data for all variables.

The analysis identified three variables highly correlated with damages to reefs:

1. Live coral cover (LCC) of the site prior to the impact is the characteristics of the reef most correlated to damages to reefs.
2. Wind-speed-at-impact, which is the characteristic of the hurricane that is most correlated with damages to reefs.
3. Sites´ exposure to dominant winds.

A well-known variable showed less correlation. However, it is included in this process as it is the most widely used variable in parametric insurance schemes.

4. Maximum wind speed.

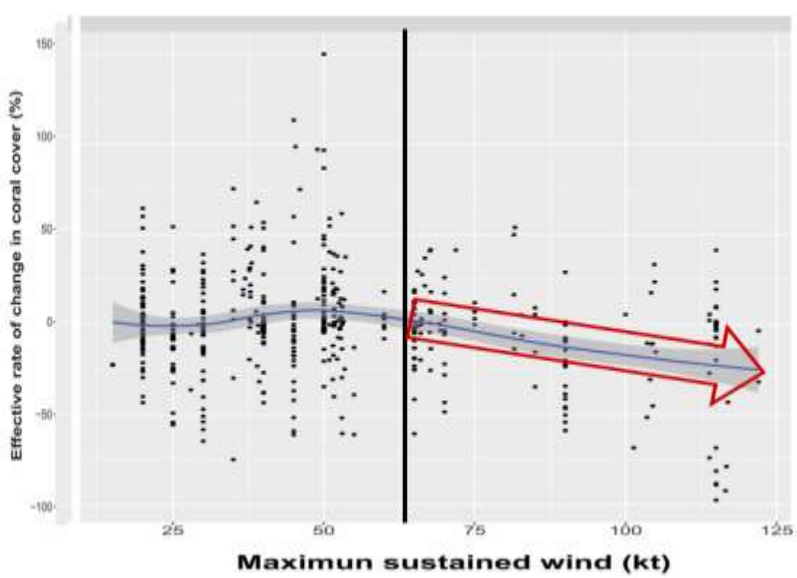
Table 4: Correlation of variables (Perez et al., 2019). P-value indicates the correlation and the lower the P-value the higher the correlation. Note: Variable = intercepto, value: b, Std. Error: Standard error , DF: degrees of freedom, t-value, p-value.

Variable (intercepto)	Value	Std. Error	DF	t-value	p-value
Initial coral cover %	-0.02	0.01	298.00	-3.90	0.0001
Maximum wind speed at impact kt cat.C: initial coral cover %	-0.02	0.01	298.00	-2.67	0.008
Exposure Windward	0.17	0.07	298.00	2.59	0.0101
Exposure middle	0.21	0.15	298.00	1.43	0.1528
Number of snapshots impacting a site	0.03	0.02	298.00	1.23	0.2213
Exposure middle:fetch medio km	0.00	0.00	298.00	-1.15	0.2526
Exposure Windward:Fetch medium km	0.00	0.00	298.00	-1.02	0.3078
Fetch medium km	0.00	0.00	298.00	0.98	0.3257
Difference sample final exit hurricane dayskt cat.L	-0.26	0.26	298.00	-0.98	0.3261
Maximum wind speed at impact kt cat.Q	-0.11	0.18	298.00	-0.62	0.5372
Maximum wind speed at impact kt cat.C	-0.05	0.10	298.00	-0.51	0.6071
Central pressure mb	0.00	0.01	298.00	-0.43	0.6643
(Intercept)	3.73	8.94	298.00	0.42	0.677
Maximum sustained wind kt	0.00	0.01	298.00	-0.40	0.6865

4.1 Maximum sustained wind speed above 60 knots is correlated with damages to reefs

Maximum sustained wind speed is the widely used in parametric insurances. The graph shows a correlation with damages, particularly above 60 knots, which shows that winds with more speed cause more damages. However, there is a wide variability in the damages to reefs showed by the dispersion of data. Among the variables assessed, wind speed is one of the least correlated variables.

Figure 3: Effective loss of live coral and maximum wind speed. Pardo et al (2019).



4.2 Wind speed at impact above 64 knots causes significant damage.

Wind speed at impact is a category of wind speed over the impacted reef. It was estimated by using the reported distances at which wind speed of 64, 50 and 32 knots (see figure 2) occurs for every hurricane (NOAA´s database: HURDAD2 (*National Oceanic and Atmospheric Administration* https://www.nhc.noaa.gov/data/)**.** Four categories of wind speed at impact were created (<34 knots, 34-50 knots, 50-64 knots and >64 knots). The value assigned to the reef corresponded to the location between the limits reported by NOAA.

Results indicate that damages to reefs increases significantly with winds above 64 knots. Data shows, however, that damages can vary significantly as there is a wide dispersion. Note also that site impacted by >64 knots are scarce compared with sites in other wind speed categories.

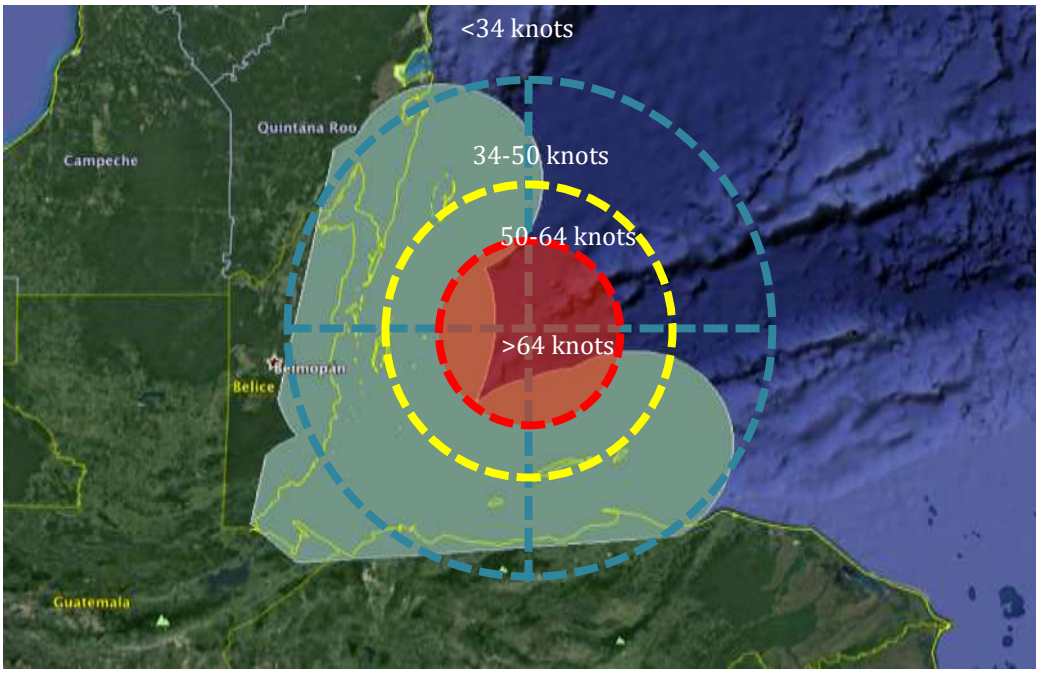
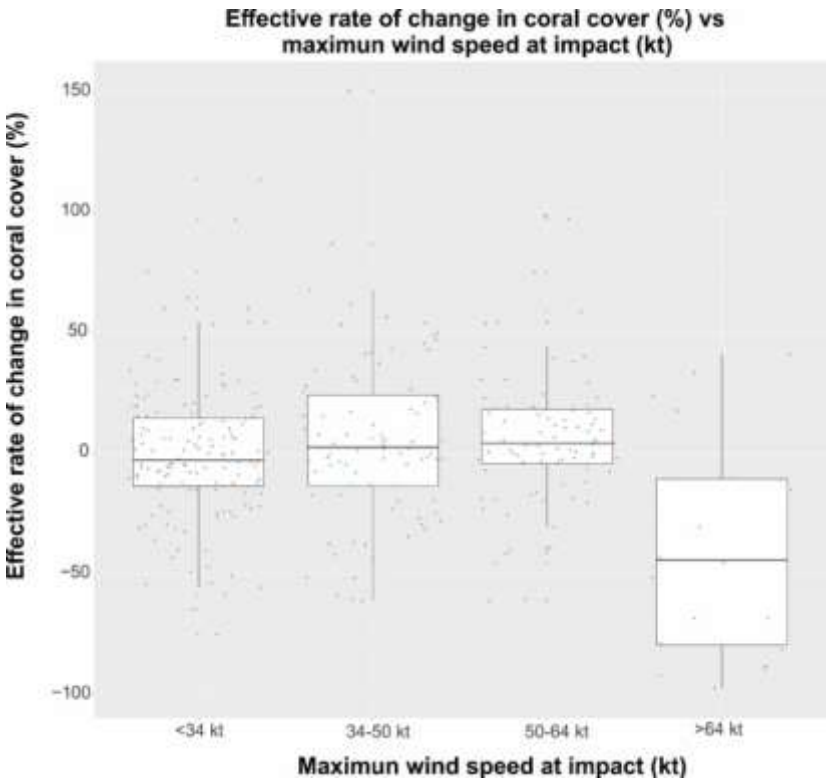


Figure 4: Wind speed at impact categories. Circumferences were estimated using the average distance from the hurricane center to the limit in which the 32, 50 and 64 knots wind speed occurs, as reported in HURDAD2 (NOAA). Distance were represented as circles altough hurricanes´ foot print are ellipses.

Figure 5: Graph shows the effective loss of coral cover according to wind category.



4.3 Reef with more coral cover will suffer more damage than reef with little coral cover

The combination of wind-speed at impact and live coral cover prior to the event has a more robust correlation. These graphics show the loss of live coral cover (net loss) caused by four categories of wind speed at impact depending on the live coral cover prior to the storm[2]. Reef with more coral cover will suffer far more damage than reefs with little coral cover. For example, sites with a critical coral cover (0-5%) and bad (5-10%) will suffer damage ranging from 0 to 2% of net live coral cover. Meanwhile, sites with good coral cover (20-40%) suffer severe net losses of live coral cover, between 8-13%, both with wind -speed above 64 knots. The impact on sites with excellent condition (+40%) is even more catastrophic, as the study shows that they have suffered a loss from 5 to 17% of net live coral cover with wind speed lower than 34 knots. Note that there is not data for sites affected by wind speed above 64 knots.

[2] The categories were defined by HRI and stakeholders for the MAR and are used in the Report Cards published every two-years, to easily assess changes in reef health.

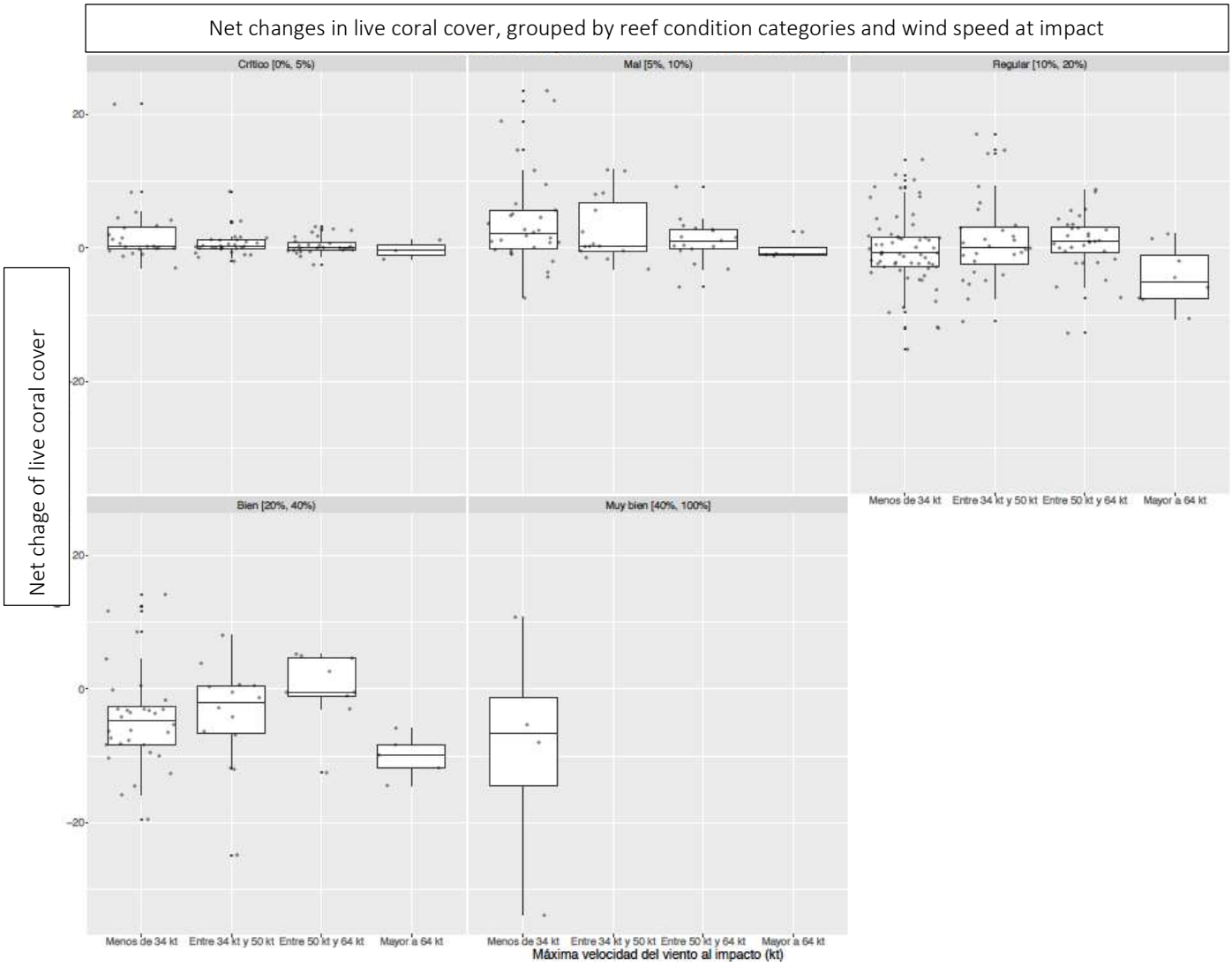
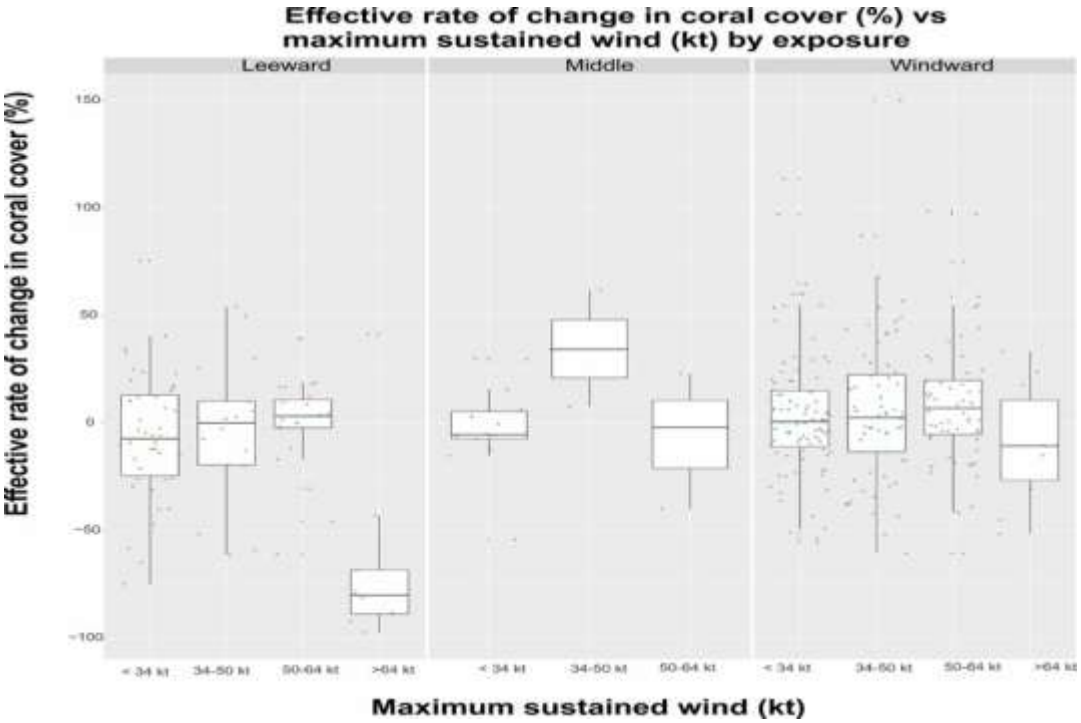


Figure 6. Changes in net live coral cover depending of live coral cover prior to the impact of a storm and by wind-speed-at impact categories. Perez et al (2019) used HRI ratings to classify Live coral cover: critical (0-5%), poor (5-10%), fair (10-20%), good (20-40%) and very good (above 40%) conditions. Wind speed at impact was classified using NOAA´s data of wind speed limits of 32, 50 and 64 knots reported in HURDAD2.

4.4 Reefs located leeward are more prone to damages that those located windward.

Location related to wind direction is correlated with damages caused by a hurricane. A location leeward will suffer more damages than a location windward. Windward reefs are directly exposed to incoming dominant winds. Leeward reefs are located in opposite direction from the dominant winds. Note, however, that hurricanes´ winds have a circular movement, therefore winds impacting a reef may come in different directions depending on the hurricane track and will change along the movement of the storm.

Figure 7: Changes in effective rated depending on the exposure to dominant wind direction.



4.5 Conclusions relevant to the selection of the parameter and threshold

The most relevant conclusions from the previous analysis are:

1. Maximum sustained wind speed increases damages above 60 knots.
2. Wind speed at impact above 64 knots causes significantly more damages to reefs than lesser winds.
3. Wind speed at impact and live coral cover is the most correlated combination of variables.
4. Wind speed at impact above 64 knots causes significantly more damage to reef with live coral cover above 20%.
5. Reefs with 40% live coral or more are more vulnerable that other with less coral cover as they are severely damaged (5 to 17% loss) with wind speeds at impact lower than 34 knots.
6. Reef located leeward tend to suffer more damages than reef located windward (dominant winds, not hurricane winds) when impacted by winds above 64 knots.

5 Estimating the loss of live coral cover

We estimated the potential loss of net live coral caused by wind speed at impact based on the initial live coral cover and the average of historical damages caused by wind speed at impact.

> The loss of live coral cover is the net loss, not a proportion of the original cover. Given that live coral cover is measured in % units, the data could mislead the reader as it may seem to indicate a % of the original coral cover. In other words, if a site has 20% of live coral cover prior to the storm, and the potential loss is 8%, the site will be left with only 12% of live coral cover (losing 40% of the pre-storm cover).

- **First**, we created a table with the average historical losses of live coral per category of HRI index (see table 5) based on the Perez et al. (2019) results.
- **Second**, we adjusted the potential loss in % of live coral cover for each site, based on the actual reported live coral cover (see table 6).
  We assumed that the average loss (AL) corresponds to mid-value of live coral cover (MV). The loss for a site (LS) would be proportional to the live coral cover of the site (LCCS). We used this formula:

$$\text{Loss of the Site} = (\text{Average Loss} \times \text{Live Coral Cover of the Site}) / \text{Med Value}$$

> **Cayo Norte example**
> Live coral cover in Cayo Norte: 12.3%
> Average loss for sites in good conditions (10-20%)= 1.8%
> Mid value of the range: 15%
> Potential net loss: 1.48%
> Estimation: 1.8% (average loss) x 12.3% (live coral cover of the site) / 15% (mid-value) = 1.48%

- **Third**, we estimated the area of live coral (hectares) which could be lost by multiplying the area of live coral cover in the site by the adjusted potential net loss (LS) (see table 7).

Table 5: Average historical net loss of live coral cover classified according to reef condition and wind speed at impact (Perez et al., 2019). N.d. means no data for that reef condition. Cero means that the average loss is cero.

HRI Index	<34 knots	34-50 knots	50-64 knots	>64 knots
Fair (10-20%)	1.8	0	0	6
Good (20-40%)	4	3	1	10
Very good (+40%)	7	n.d.	n.d.	n.d. (10)*

*We assigned 10% average loss for very good condition under 64 knots, using the value of the good condition, as we needed values above 64 knots for all categories.

Table 6: Adjusted potential net loss of live coral cover based on historical losses classified by reef condition category and "wind speed at impact" categories (Perez et al., 2019). The historical average loss value was adjusted with the reported live cove for the site. Sites marked in light orange are those with the highest net loss.

Insured site name	% of live coral cover	<34 knots	34-50 knots	50-64 knots	>64 knots
Cayo Norte	12.3	1.48	0.00	0.00	4.92
Las Pozas	17.7	2.12	0.00	0.00	7.08
Hol Chan	10.7	1.28	0.00	0.00	4.28
Turneffe	16.8	2.02	0.00	0.00	6.72
Corona Cayman	44.0	7.70	2.75	0.55	11.00
Utila	18.5	2.60	1.34	0.27	6.85
• Turtle Harbour - Rock Harbour		2.75	1.72	0.34	6.87
• White Water		2.05	0.00	0.00	6.84
Roatan	30.28	4.93	2.40	0.48	9.52
• Cordelia		7.18	2.56	0.51	10.25
• French Cay		5.11	3.19	0.64	12.77
• Sandy Bay West End		6.56	4.10	0.82	8.20
• Santa Elena		2.06	0.00	0.00	6.88
Guanaja	19.3	2.32	0.00	0.00	7.72
Cayos Cochinos	16.1	1.93	0.00	0.00	6.44

As stated previously, we estimated the area of live coral lost by multiplying the % of the potential net loss by the area of live coral cover calculated for the site (see table). The area lost is the result of the extent of the damages and the extent of the coral cover. Turneffe and Guanaja are the sites with larger areas as they are the largest sites. The potential loss in hectares is used to estimate the level of effort and costs needed to implement a repair. The area also makes explicit the extent of the possible damage caused by hurricanes.

Table 7: Estimated live coral cover loss in hectares per site(net live coral cover multiplied by adjusted loss).

Insured site	Estimated net live coral cover (ha)	Estimated loss of live coral cover caused by wind speed at impact (ha)				Loss - % of original cover
		<34 knots	34-50 knots	50-64 knots	>64 knots	%
Cayo Norte	20.06	2.41	0.00	0.00	8.02	40
Las Pozas	315.87	37.90	0.00	0.00	126.35	40
Hol Chan	112.86	13.54	0.00	0.00	45.15	40
Turneffe	1,187.95	142.55	0.00	0.00	**475.18**	40
Corona Cayman	464.12	81.22	29.01	5.80	116.03	25
Utila	75.70	10.42	5.40	1.08	27.55	36
Turtle Harbour - Rock Harbour	64.77	8.64	5.40	1.08	21.59	33
White Water	14.91	1.79	0.00	0.00	5.96	40

Insured site	Estimated net live coral cover (ha)	Estimated loss of live coral cover caused by wind speed at impact (ha)				Loss - % of original cover
		<34 knots	34-50 knots	50-64 knots	>64 knots	%
Roatan	224.37	36.51	17.80	3.56	64.01	29
Cordelia	38.47	6.73	2.40	0.48	9.62	25
French Cay	38.69	5.16	3.22	0.64	12.90	33
Sandy Bay West End	73.00	19.47	12.17	2.43	24.33	33
Santa Elena	42.91	5.15	0.00	0.00	17.17	40
Guanaja	850.36	102.04	0.00	0.00	**340.14**	40
Cayos Cochinos	232.98	27.96	0.00	0.00	93.19	40

6 Estimating the cost of repairing the reef

Whiterock (2019), under a contract with MARFund and with technical assistance from TNC, developed a tool to estimate the cost of repairing the reef and restoring live coral cover to a certain extent. The tool details all expenses (boats, divers, tanks, food, materials) needed to repair an area covered by 3 brigades. The cost of repairing such area is then multiplied by the estimated area damaged in each site.

In most cases, the cost to repair and restore all the damaged area is way above the current levels of expenditure in reef conservation. The extent of the repair will depend on the funds available and the scope of the intervention according to the objectives of the managers of the reef. Therefore, the costs are also expressed in three levels of intervention, showing the costs to repair 25%, 50% or 100% of the damaged area.

Besides funds, another limitation to implement repair actions is the existing local capacity to conduct them. Therefore, we also estimated the costs of mobilizing the capacity that would be in place by 2020, consisting in three brigades (each of 10 Pax) for 60 days after the storm per site. We also calculated three levels of intervention, with 25%, 50% and 100% for such effort.

The estimation of the cost to repair follows the phases defined in the Post Storm Protocol. Those phases of intervention are:

1. Immediate response:
    a. Rapid damage assessment: 2-5 days to evaluate the damages, visiting priority sites, identify damages and plan a response.
    b. Primary response: cleaning debris, attaching big fragments and stabilizing coral colonies.
    c. Secondary response: collecting smaller fragments and establishing in nurseries, for future colonization. Also, repair of structural damages.
    d. Post-storm response evaluation: phase to evaluate the damages to the reefs, the results of the primary and secondary response, and development of a restoration plan for the next 2-5 years to support the recovery of the reef.
2. Mid-term repair: implementation of the restoration plan.

Table 8: Projected cost of immediate response based on the area impacted.

Site	Projected loss of live coral cover area (ha) above 64 kn	USD Cost of response – 25%	USD Cost of response – 100%
C. Norte - Chinchorro	8.02	53,792	156,830
Las Pozas Xcalak	126.35	310,725	1,174,609
Hol-Chan	45.15	224,174	779,307
Turneffe	**475.18**	**1,085,474**	**3,999,051**
Corona cayman PM	116.03	216,204	774,841
Utila	27.55	98,220	302,579
Roatán	64.01	213,215	755,288
Guanaja	**340.14**	**833,559**	**3,132,258**
Cayos Cochinos	93.19	212,426	734,559
Total	**3,484**	**3,247,790**	**11,809,322**

Figure 8. Projected cost of immediate response based on the area impacted.

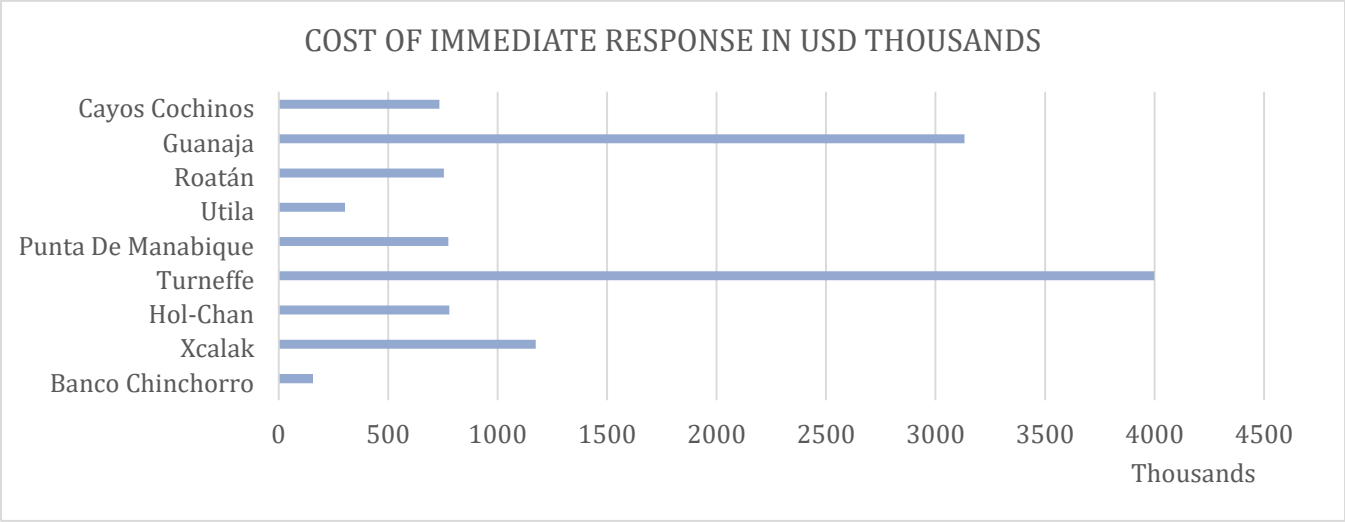
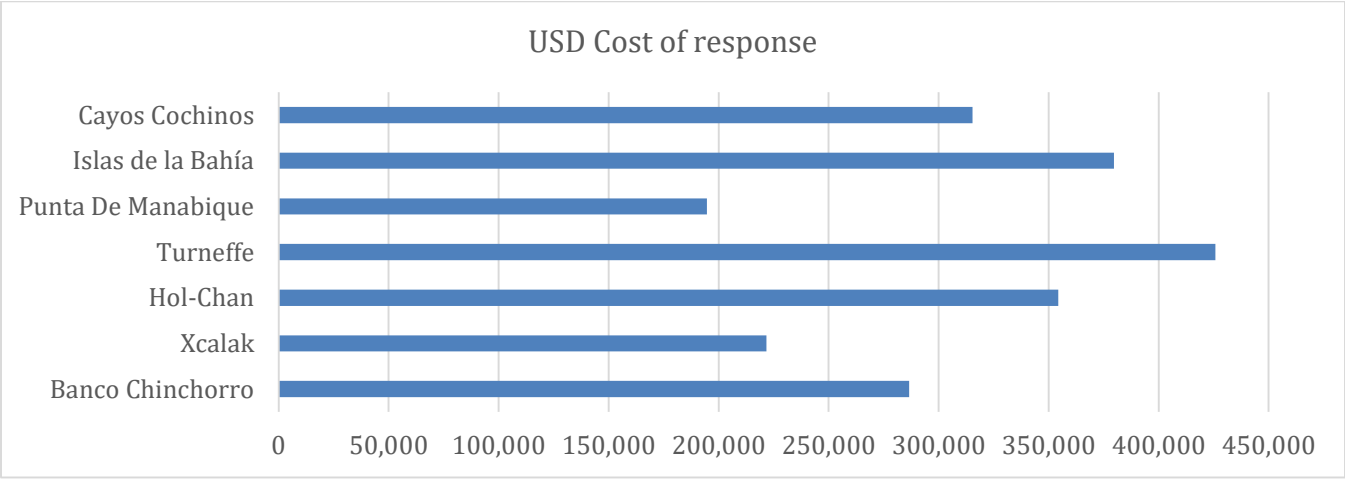


Table 9: Projected cost of immediate response based on 3 brigades (30 brigadists) per site working 60 days after the storm.

Site	Loss of live coral cover above 64kn (ha)	USD Cost of Intervention – 25%	USD Cost of Intervention – 100%
Banco Chinchorro	8.02	91,016	286,602
Xcalak	126.35	69,474	221,778
Hol-Chan	45.15	118,295	354,313
Turneffe	475.18	142,125	**425,742**
Punta De Manabique	116.03	71,920	194,650
Utila	27.52		
Roatán	70.58	122,009	**379,668**
Guanaja	340.14		
Cayos Cochinos	93.19	105,557	315,464
Total	**1,302**	**964,413**	**2,937,553**

Figure 9: Projected cost of immediate response based on 3 brigades (30 brigadists) per site working 60 days after the storm



7 Approach to define scenarios of insurance polygons

We developed distinct scenarios of polygons based on the main conclusions of how hurricanes damage reefs. The advantages and disadvantages of these scenarios can be compared by stakeholders and buyers to decide the product that better fits their needs and budget.

The most relevant conclusions from the analysis in page 14 are:

1. Maximum sustained wind speed increases damages above 60 knots.
2. Wind speed at impact above 64 knots causes significantly more damages to reefs than lesser winds.
3. Wind speed at impact and live coral cover is the most correlated combination of variables.
4. Wind speed at impact above 64 knots causes significantly more damage to reef with live coral cover above 20%.
5. Reefs with 40% live coral or more are more vulnerable that other with less coral cover as they are severely damaged (5 to 17% loss) with wind speeds at impact lower than 34 knots.
6. Reef located leeward tend to suffer more damages than reef located windward (dominant winds, not hurricane winds) when impacted by winds above 64 knots.

To address these conclusions, we proposed the following options:

1. A series of polygons limited to the insured sites and using 64 knots as trigger. For reef with live coral cover above 40%, the proposed trigger is 50 knots.
2. Polygons using a buffer around the sites of interest considering a distance from the eye of the hurricane in which the 64 knots wind speed generally occurs. The parameter would be maximum wind speed and the trigger 105 knots. This approached was used in the Mexican Caribbean insurance.
3. Assign a lower value of the parameter for Cordelia and French Cay (in Roatan, Bay Islands) and Corona Cayman, as they have live coral cover above 40%.

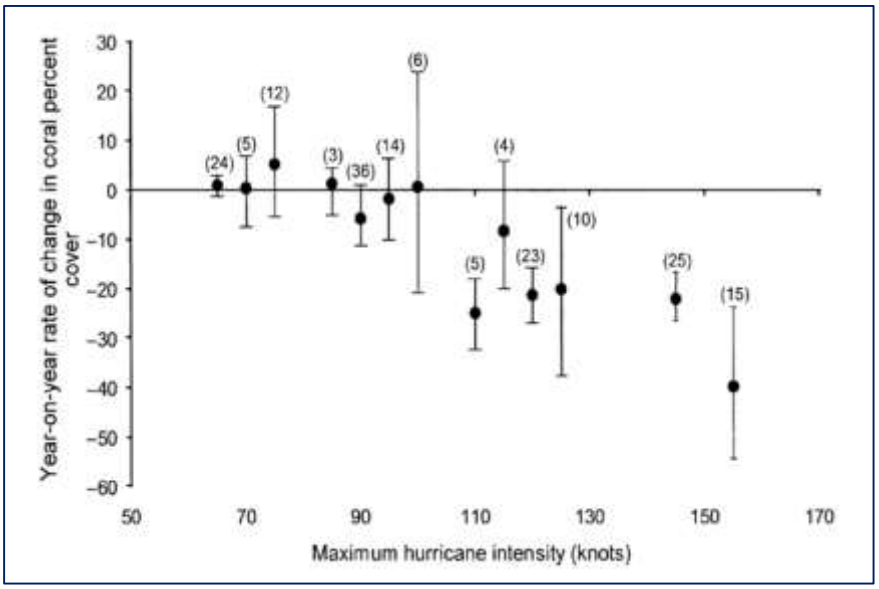
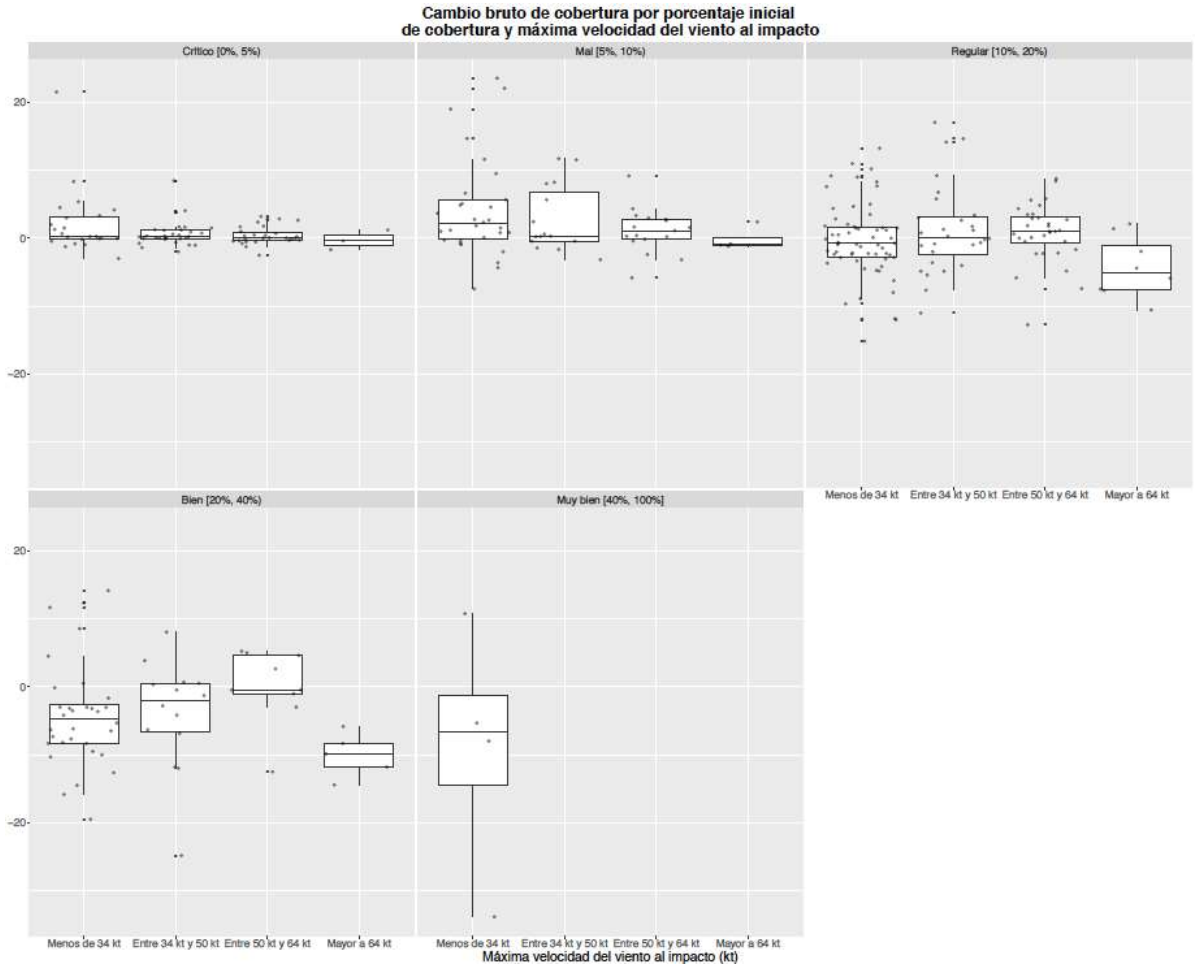


Figure 11: Relationship between maximum wind speed of the hurricane with damages to live coral cover (Gardner et. al., 2005)

Figure 10: Relationship between wind speed at impact of a hurricane with damages to live coral cover (Perez et al. 2019)



To estimate the size of the polygons around the selected reefs at which maximum wind speed at the eye could affect the reef we used distance from the center of the hurricane to the 64 knots limit. We calculated the average distances from the eye of a hurricane to the reported wind speeds (34, 50 and 64 knots using the data published by NOAA for hurricanes between 2004 to 2017. Hurricanes shape is elliptical, therefore distance to the Northeast (NE) (50mn) and Northwest (NW) (46nm) are larger than the South east (SE) distance (41.7nm) and much larger than Southwest (SW) distance (30.3nm). Reefs in the Mesoamerican Reef will be impacted mostly by winds NW (46) and SW (30) from the center of hurricane, therefore we proposed a buffer of 45 nm. This buffer reduces the risk of suffering damages and not triggering a payout.

Figure 9: Maps showing a hypothetical extent of a hurricane with the average distance of the 64, 50 and 32 knots wind speeds. The circles show distances of 45, 70 and 126 nautical miles from a hurricane eye.

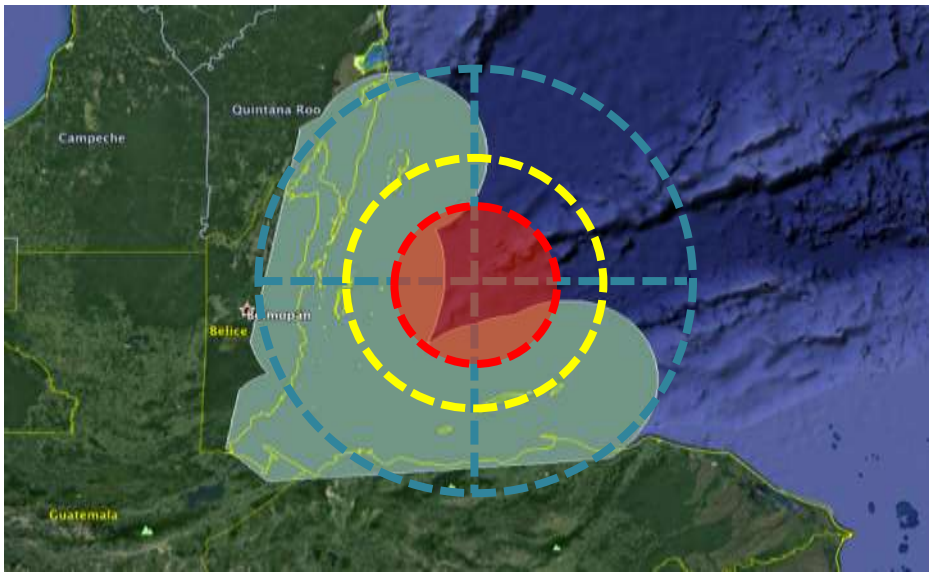


Table 10: Distance (nautical miles) from the hurricane eye to the limit of the wind speed, reported by NOAA between 2004-2017, classified by maximum wind speed clustered every 20 knots[3]. The groups do not correspond to any hurricane category.

	RADIUS IN NAUTICAL MILES						
		NE	NW	SE	SW		
	Maximum wind speed (knots)	Average	Average	Average	Average	Average of averages	Proposed buffer
64 kn	Group 1 (60-80)	34	33	36	31	33	
	Group 2 (85-100)	39	32	35	27	33	
	Group 3 (105-120)	49	42	41	32	41	45
	Group 4 (125-140)	50	44	41	30	41	45
	Group 5 (145-160)	49	46	43	30	42	45
50 kn	Group 1 (60-80)	67	57	67	55	62	
	Group 2 (85-100)	70	57	70	48	61	
	Group 3 (105-120)	83	70	83	53	72	70
	Group 4 (125-140)	86	73	86	50	74	70
	Group 5 (145-160)	85	76	85	48	74	70
34 kn	Group 1 (60-80)	148	116	141	106	128	
	Group 2 (85-100)	136	110	124	93	116	
	Group 3 (105-120)	155	130	138	100	131	126
	Group 4 (125-140)	158	136	123	92	127	126
	Group 5 (145-160)	152	141	119	91	126	126

[3] NOAA dataset reports maximum windspeed every 5 knots, therefore the groups coarsely correspond to the Saffir-Simpson hurricanes categories.

8 Insurance polygons scenarios

1. Discrete polygons for each proposed site.

This scenario limits the insurance polygons to the proposed sites, except in Bay Islands where the 8 polygons were clustered in one polygon. This option allows for distinct payouts for each site.

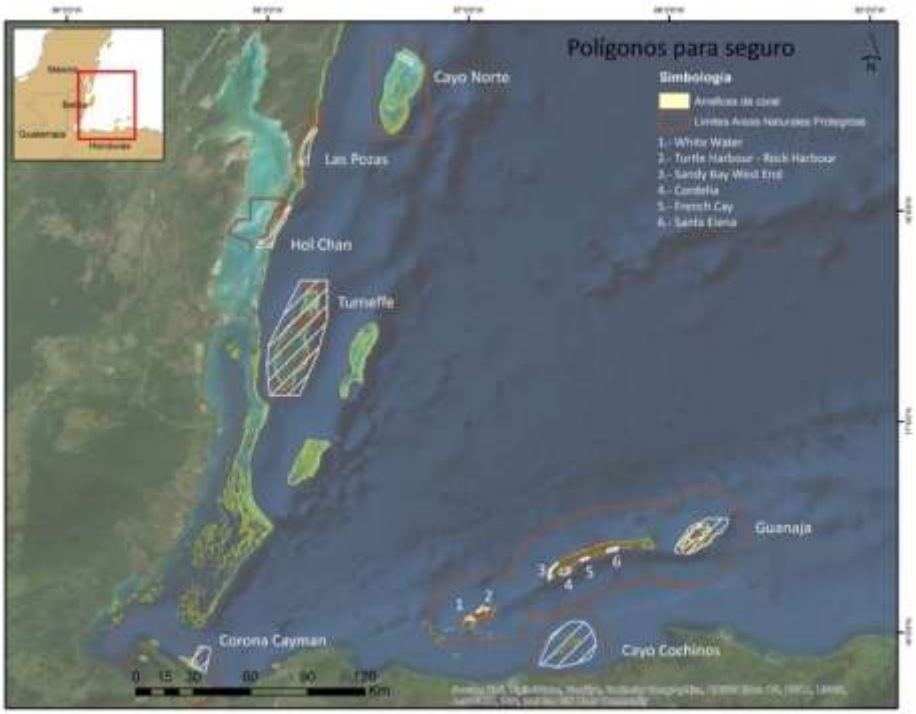


Figure 10: Insurance polygons for the sites to be insured. They correspond exactly to the sites proposed.

2. A polygon with 45 nautical miles buffer.

This polygon has a buffer of the average distance from the hurricane eye to wind speeds of 64 knots (45 nm). The trigger would be a wind speed of 105 knots (mid category 3 hurricanes) following results from Gardner et a.l (2005). This option allows for one payout for the region, and a distribution scheme should be devised.

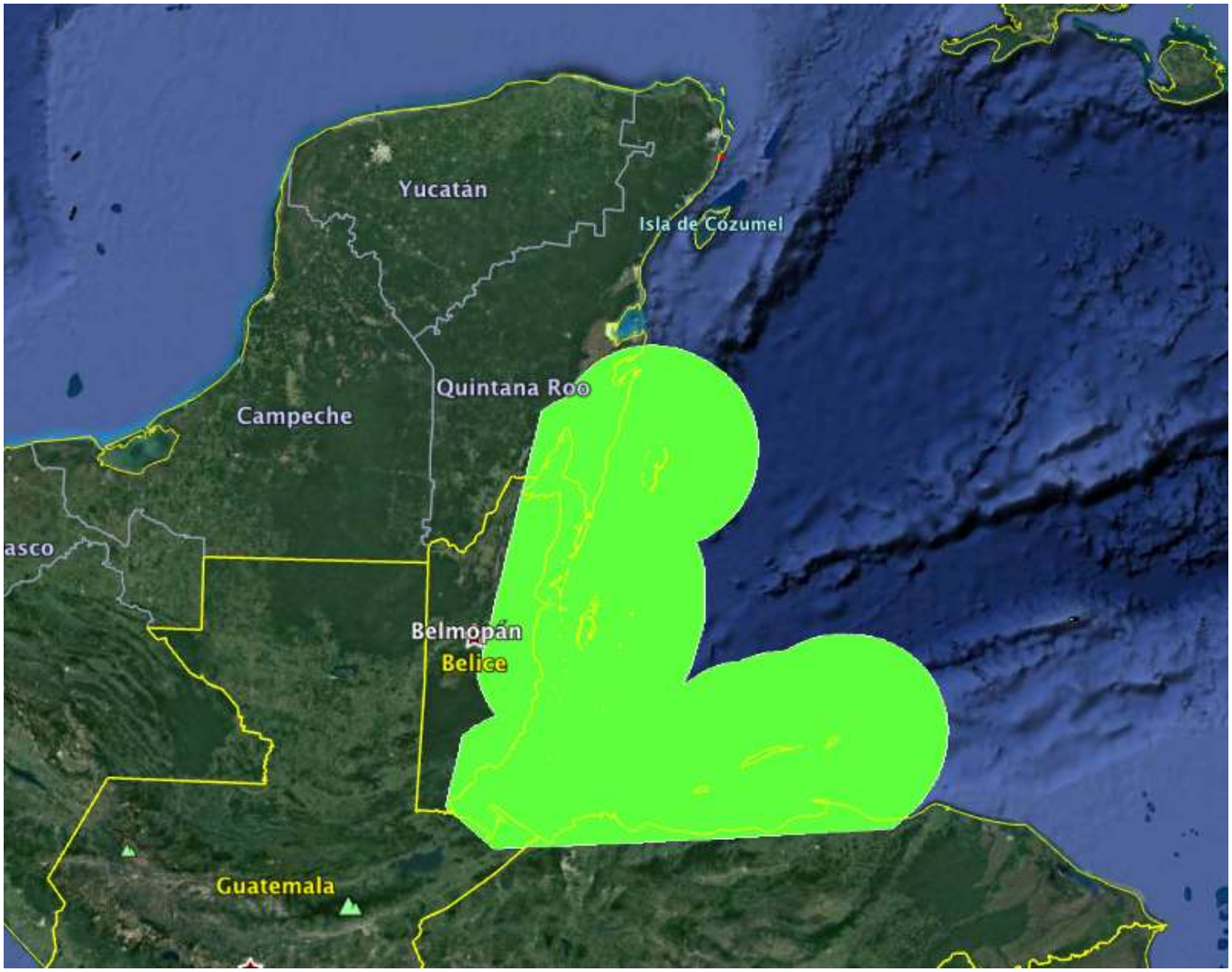


Figure 11: Polygon with a buffer of 45 nautical miles around all sites.

3. A polygon with 45 miles plus distinct polygons around critical reefs.

This option establishes two distinct polygons: one around Cordelia and French Cay (Roatan, Islas de la Bahía) and another one Corona Cayman (Punta Manabique), given these have more 40% of live coral cover and are more vulnerable to wind with less than 64 knots. The trigger for those distinct polygons will be 93 knots (lower limit for category 3 hurricanes). This option allows for one payout for the region and two for the other two polygons. A distribution scheme should be devised for the larger polygon.

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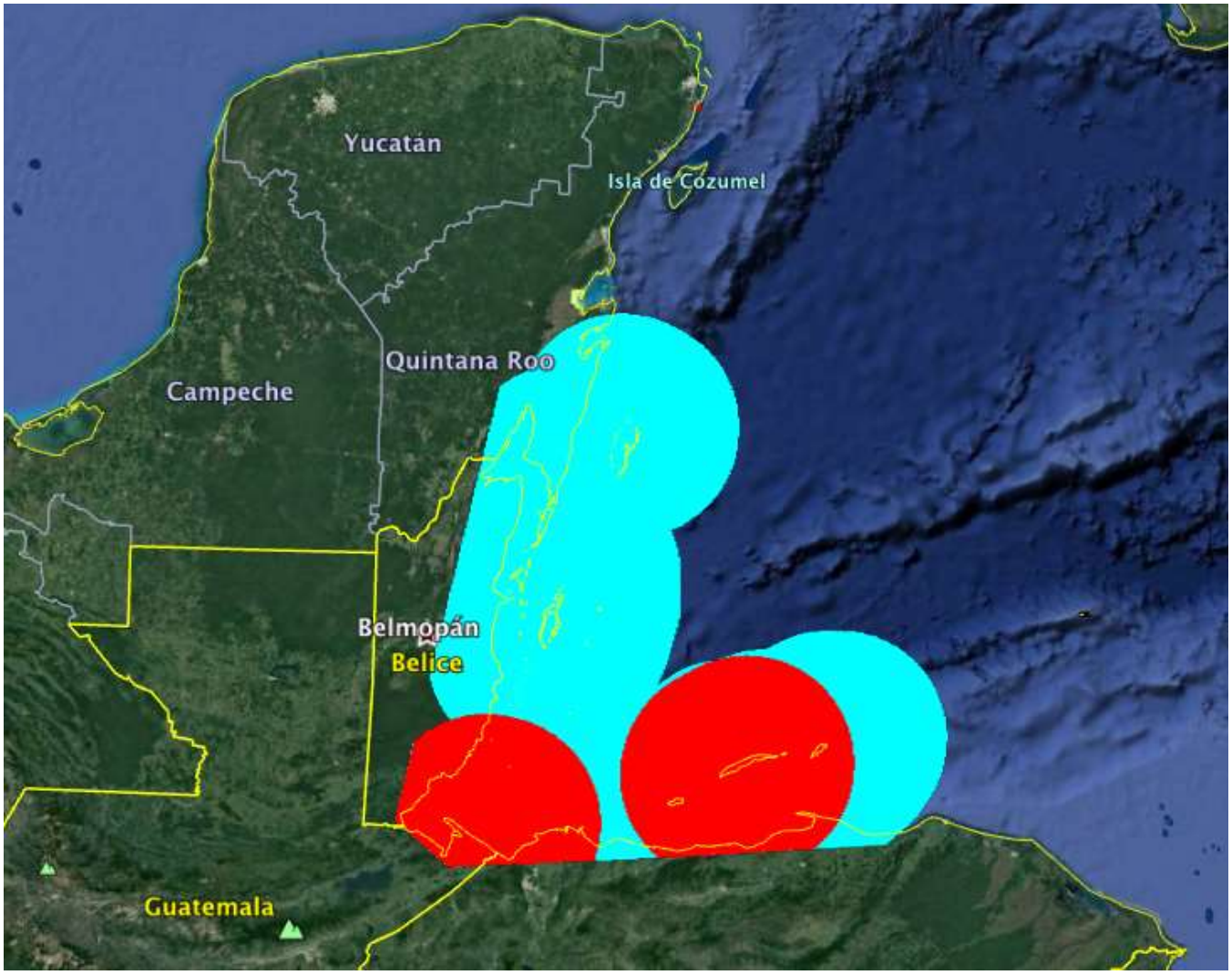


Figure 12: Polygon with a buffer of 45 nautical miles around all sites with two polygons (red) around the vulnerable sites in Corona Cayman (Guatemala) and Frech Harbour and Cordelia (Bay Islands, Honduras).

4. Distinct polygon with 45 miles for each proposed site.

This option creates a distinct polygon for each in site. This option allows for distinct payouts for each site. It is highly that 3-4 sites will be impacted by the same hurricane as they are closed-by compared to the extent of a hurricane

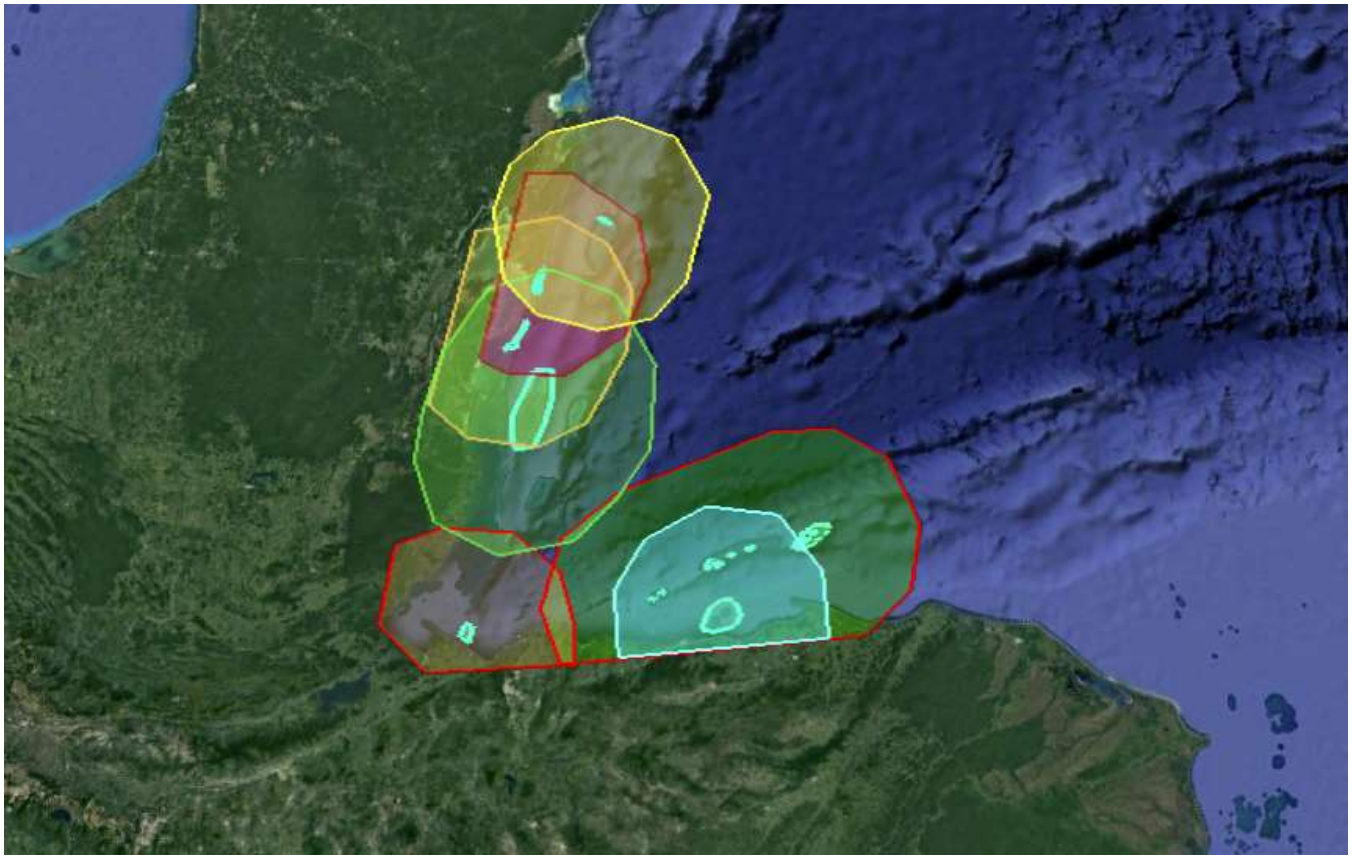


Figure 13: Seven polygons with a buffer of 45 nautical miles around the seven sites to be insured.

5. Distinct polygon with 45 miles for country.

This option creates a distinct polygon for each country, clustering the two sites of each and the one in Guatemala. This option allows for distinct payouts for each country. It is very likely that both sites will be impacted by the same hurricane as they are closed by compared to the extent of a hurricane.

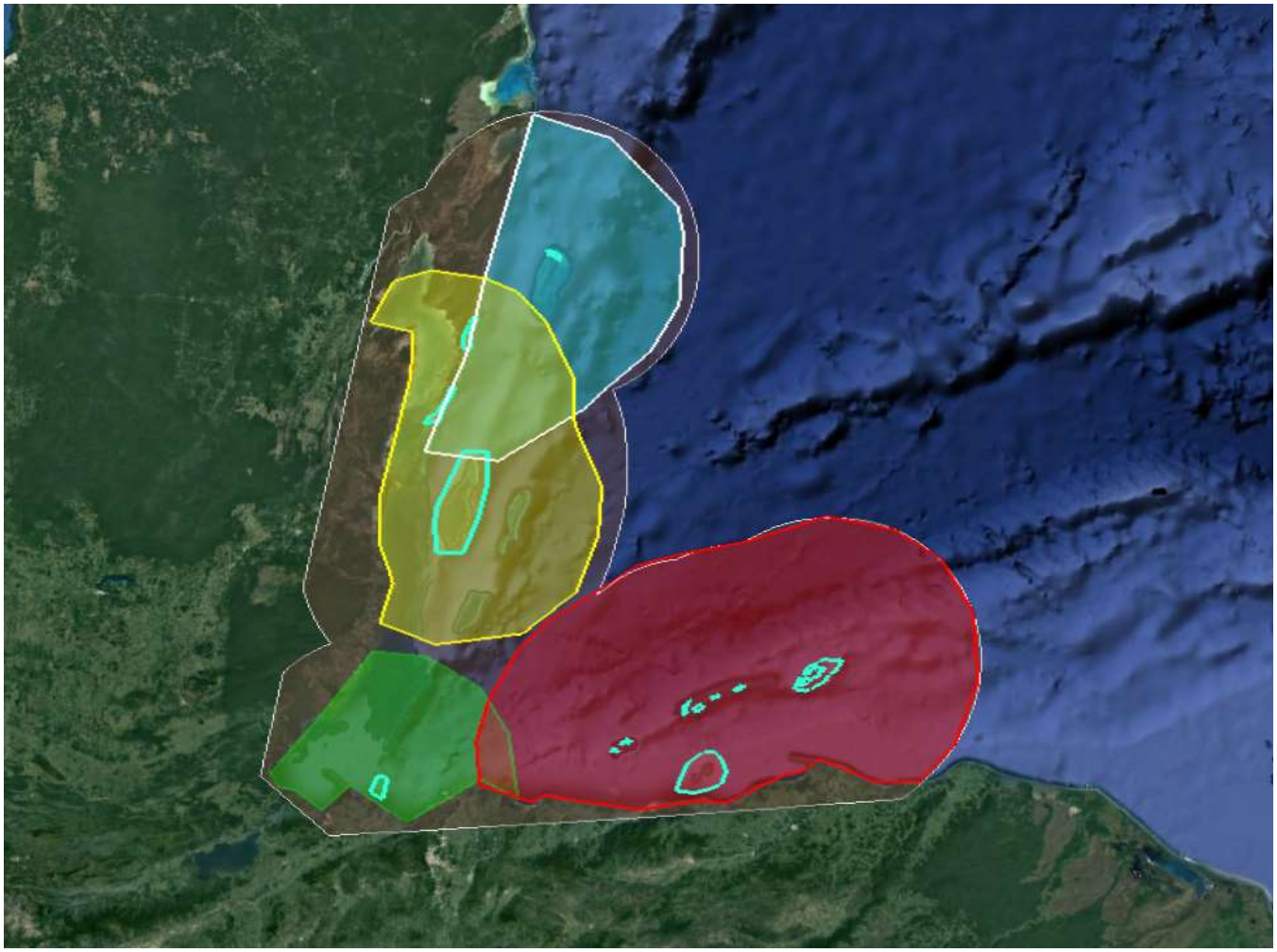
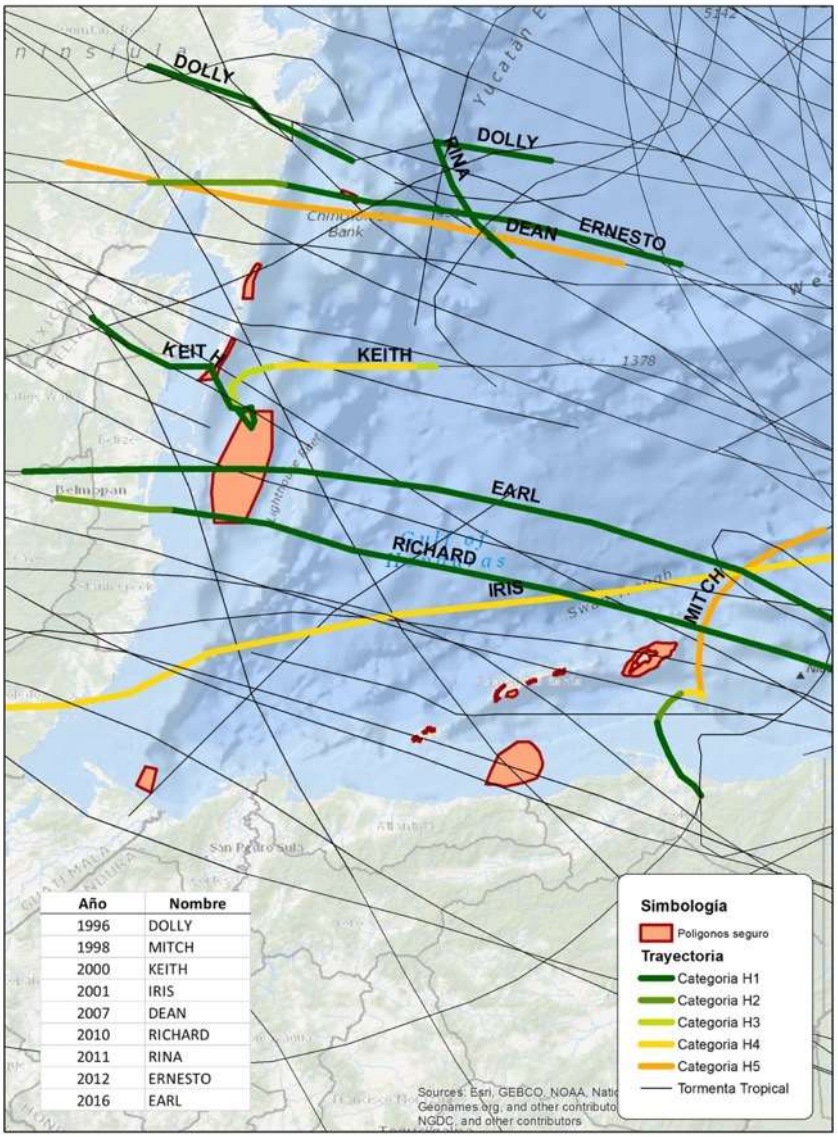


Figure 14: Four polygons with a buffer of 45 nautical miles around clusters of the sites per country. Mexico (blue), Belize (yellow), Guatemala (green) and Honduras (red).

8.1 Analysis of the impact of historical hurricanes in the proposed polygons

We conducted an analysis of the maximum wind speed of historic hurricanes which hit the region during the last 23 years (1996-2018) to assess which ones would had hit the proposed polygons and might have triggered the insurance (H5 - orange and H4 -yellow), depending on the threshold to be selected. We measured the distance from the site the hurricane track and if less than 45nm we considered the site as impacted by the hurricane. We assigned the highest storm category passing at or closer to 45nm

Figure 15: Hurricane and storms tracks since 1990 and their impact on the insured sites.



Año	Nombre
1996	DOLLY
1998	MITCH
2000	KEITH
2001	IRIS
2007	DEAN
2010	RICHARD
2011	RINA
2012	ERNESTO
2016	EARL

Figure 15: Storms and hurricane tracks and polygons of insured sites.

Figure 16: Hurricane and storm tracks by category and their impact on the country´s polygons.

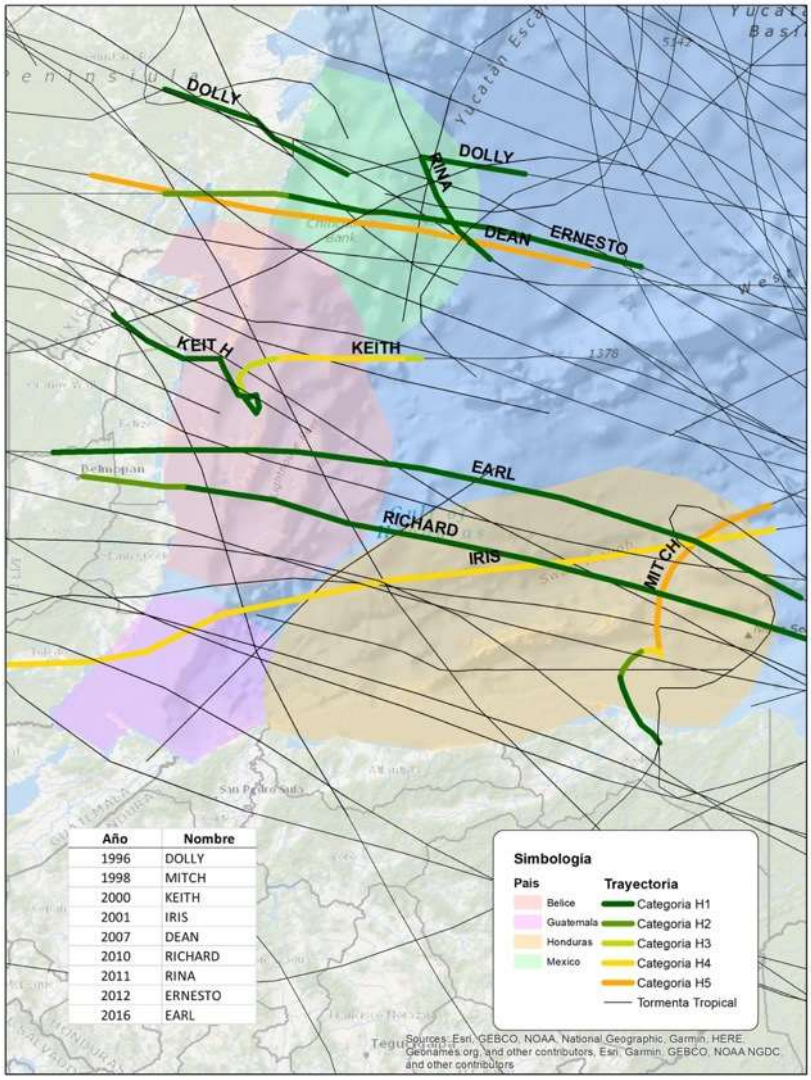


Table 11: Hurricanes who would have hit the one polygon scenario.

Year	Name	**One polygon**
1996	Dolly	H1
1998	Mitch	H5
2000	Keith	H4
2001	Iris	H4
2007	Dean	H5
2010	Richard	H1
2011	Rina	H1
2012	Ernesto	H1
2016	Earl	H1

Table 12: Hurricanes hit the country´s polygons.

Hurricane		Maximum wind speed			
Year	Name	**Mexico**	**Belize**	**Honduras**	**Guatemala**
1996	Dolly	H1			
1998	Mitch			H5	
2000	Keith	H4	H4		
2001	Iris			H4	H4
2007	Dean	H5	H5		
2010	Richard		H1	H1	
2011	Rina	H1			
2012	Ernesto	H1			
2016	Earl		H1	H1	

Table 13: Hurricanes hitting the sites´ polygons. The results are the same for sites with a 45 nm buffer against hurricane track, and for sites with no buffer against 64 knots wind-at-impact.

Hurricane		Maximum wind speed						
Year	Name	**Cayo Norte**	**Las Pozas**	**Hol Chan**	**Turneffe**	**Islas de la Bahía**	**Cayos Cochinos**	**Cayo Corona**
1996	Dolly	H1	H1					
1998	Mitch					H5	H2	
2000	Keith		H4	H4	H4			
2001	Iris				H4	H4		H4
2007	Dean	H5	H5	H5				
2010	Richard			H1	H1	H1		
2011	Rina	H1						
2012	Ernesto	H1	H1					
2016	Earl			H1	H1	H1		

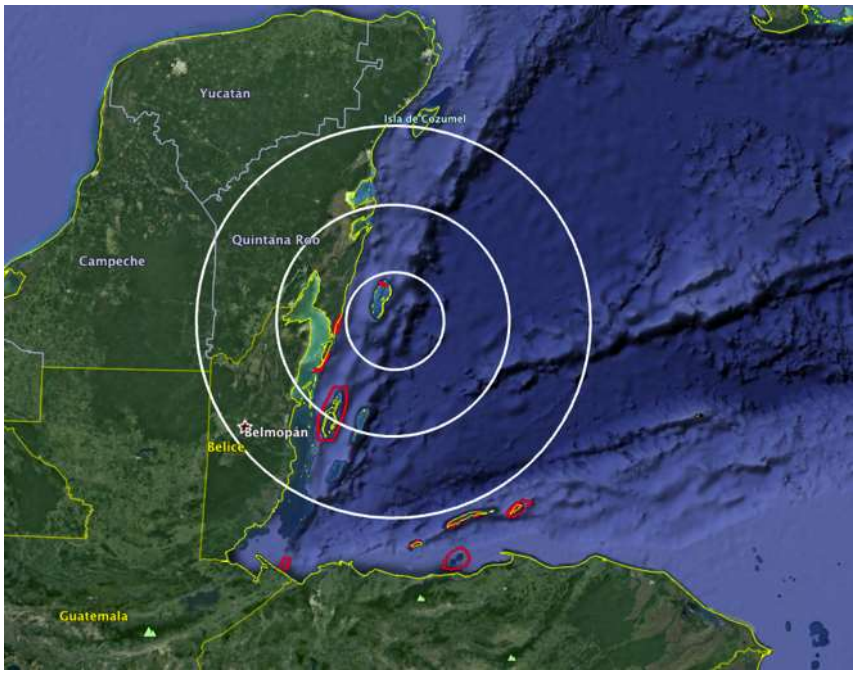


Figure 17: Visualization of the hurricane extent using the average radius of wind speeds at 64, 50 and 34 knots. It shows have this hypothetical hurricane would have impacted three polygons (Cayo Norte, Las Pozas and Hol Chan) given the size of a typical hurricane and the proximity of the insured sites.

9 Payout scenarios

We created scenarios of payouts considering the following variables:

1. The proposed parametric insurance polygon.
2. The mutualization of the risk or not among the different polygons.
3. The parameter used, either máximum wind speed or wind speed at impact.

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1. **Each site with a payout triggered by 64 knots of wind speed at impact. Bay Islands and Corona Cayman shall be triggered by 50 knots (see figure 17)**
    - Parameter: wind speed at impact.
    - Trigger: 50 knots for special polygons and 64 for the larger polygons.
    - Each site has a distinct payout.

Table 20: Payout per site.

Sites	Liability Limit USD
Cabo Norte	300,000
La Poza	300,000
Hol Chan	300,000
Turneffe	300,000
Corona Cayman	300,000
Bay Islands	300,000
Cayos Cochinos	300,000
Total	2,100,000

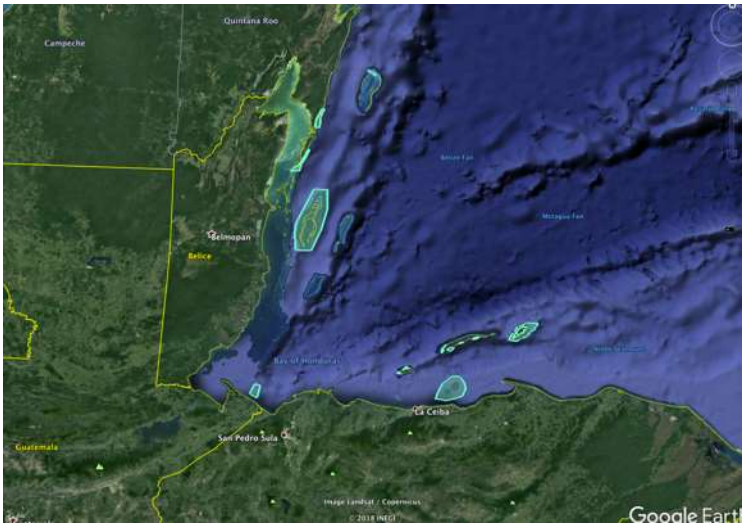

Figure 18: Map of the polygons of insured sites.

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2. **Combined payout and triggers among the 7 sites (see figure 18)**
    - Parameter: wind speed at impact.
    - Trigger: 50 knots for special polygons and 64 for the larger polygons.
    - Payout increases along wind speed.
    - The amount of the payout depends on the numbers of site-polygons hit by wind speed at impact.
    - Payout increases at different values.
    - The liability limit is lower than with the individualized policies.

Table 21: Payout by combinations of sites.

Sites	50 knots	64 knots	80 knots
1	150,000*	150,000	300,000
2		300,000	600,000
3		450,000	900,000
4		600,000	1,200,000
5		750,000	1,500,000
Liability limit			1,500,000

3. **Payout for a MAR-wide polygon and two special polygons.**

- Parameter: Maximum wind speed.
- Trigger: 90 knots for special polygons and 105 for the larger polygons.
- Payout increases along wind speed.
- It increases the possibility of a payout given the size of the polygon.
- It also requires a scheme to distribute the funding among sites.

Table 22: Payout for one polygon per maximum wind speed.

Maximum Wind Speed	USD
90* knots	150,000
105 knots	300,000
120 knots	600,000
137 knots	1,200,000
Liability limit	1,200,000

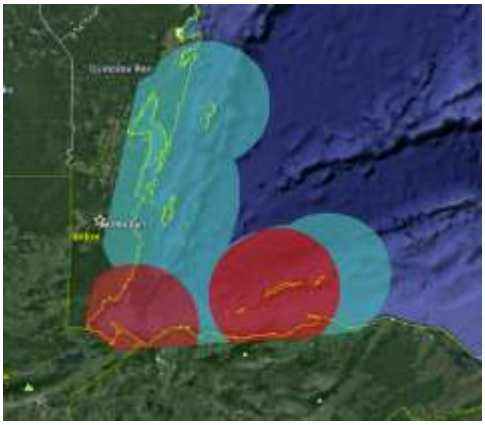

Figure 19: Polygon encompassing all 7 sites and distinct polygons around vulnerable sites. All with 45 nautical miles buffer around sites

4. **Payout for polygons with 45 miles for each proposed site, mutualized risk.**

- Parameter: Maximum wind speed
- Trigger: 90 knots for vulnerable site and 105 knots for others
- Payout increases as the numbers of sites hit and with wind speed.

Table 23: Payout per combination of polygon for each site.

Sites	90 knots	105 knots	120 knots
1	150,000*	150,000	300,000
2		300,000	600,000
3		450,000	900,000
4		600,000	1,200,000
5		750,000	1,500,000
Liability limit			1,500,000

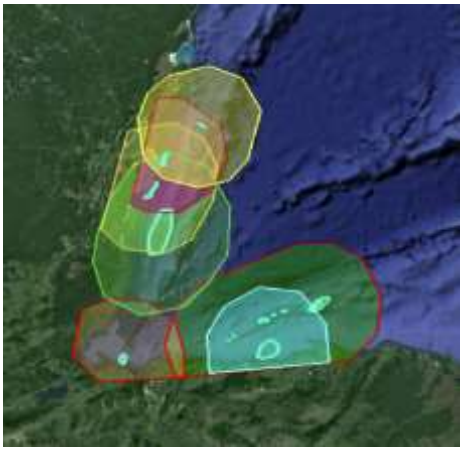

Figure 20: Polygons with 45 nautical miles buffer around seven sites

5. **Payout for country polygons, mutualized risk.**

- Parameter: Maximum wind speed
- Trigger: 90 knots for vulnerable site and 105 knots for others
- Payout increases as the numbers of sites hit.

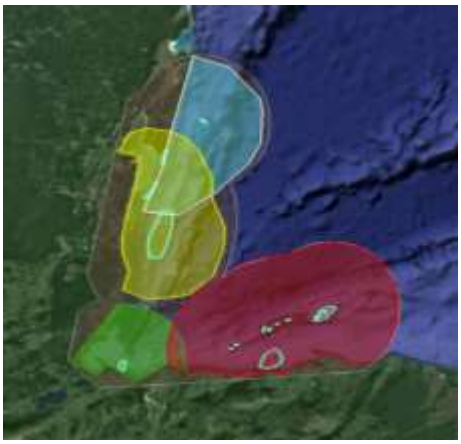

Table 24: Payout per combination of polygons per country.

Sites	90 knots	105 knots	120 knots
1		300,000	500,000
2		500,000	1,000,000
3		900,000	1,500,000
Gua	100,000	150,000	250,000
Liability limit			1,500,000

Figure 21: Polygons per country with a buffer of 45 nm around the sites in the country.

6. **Payout for country polygons, not mutualized risk.**

- Parameter: Maximum wind speed.
- Trigger: 90 knots for vulnerable site and 105 knots for others.
- Distinct payout for each country polygon hit.

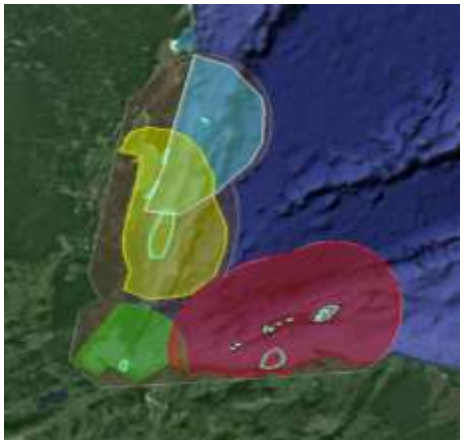

Table 25: Payout per polygon per country, not combined.

Sites	90 knots	105 knots	120 knots
Belize		300,000	500,000
Mexico		300,000	5,00,000
Honduras	100,00	300,000	500,000
Guatemala	100,000	150,000	250,000
Liability limit			1,750,000

Figure 22: Polygons per country with a buffer of 45 nm around the sites in the country.

10 Analysis of scenarios

We propose a framework to assess the different scenarios to choose the one that better meets the needs of the stakeholders

Table 26: Criteria to assess the different scenarios.

	Polygons for each proposed site without a buffer	Polygon with 45 nm buffer + distinct polygons	Polygons per country with 45 nm buffer	Polygons per site with 45 nm buffer
Criteria to assess the options				
Cost of the policy (% of payout)				
Distribution of the cost of the policy among stakeholders				
Probability of a triggering event				
Efficiency in the distribution of funds to areas impacted				
Mutualization of risk				

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12 ANNEX: SITES DETAILED INFORMATION

Table 27: Cost of repair of all the damaged area. Cost of immediate response, in USD.

Cost of Immediate Response	Live Coral Cover %	Area with Lcc (Ha)	Projected % loss	Project area loss	Intervened Area (100%)	USD Cost of response	USD Cost of response	USD Cost of response
Site	%	Ha	%	Ha	Ha	25% level	50% level	100% level
Banco Chinchorro	12.30	20.06	4.92	8.02	8.02	53,792	88,138	156,830
Xcalak	17.70	315.87	7.08	126.35	126.35	310,725	598,687	1,174,609
Hol-Chan	10.70	112.86	4.28	45.15	45.15	224,174	409,218	779,307
Turneffe	16.80	1187.95	6.72	475.18	190.07	1,085,474	2,056,666	3,999,051
Punta De Manabique	44.00	464.12	11.00	116.03	58.01	216,204	402,416	774,841
Utila	18.85	75.70	6.85	27.52	11.01	98,220	166,340	302,579
Roatán	30.28	224.37	9.52	70.58	28.23	213,215	393,906	755,288
Guanaja	19.30	850.36	7.72	340.14	136.06	833,559	1,599,792	3,132,258
Cayos Cochinos	16.10	232.98	6.44	93.19	37.28	212,426	386,470	734,559
Total		3,484		1,302	640	3,247,790	6,101,634	11,809,322

Table 28: Cost of repair of all the damaged area. Cost of mid-term response in USD.

Mid-Term response Cost								
Site	Live Coral Cover %	Area with Lcc (Ha)	Loss of Projected Lcc	Area with Loss of Lcc	Intervened Area (100%)	USD Cost of response	USD Cost of response	USD Cost of response
	%	Ha		Ha	Ha	25%	50%	100%
Banco Chinchorro	12.30	20.06		8.02	N/A	147,281	269,106	512,757
Xcalak	17.70	315.87		126.35	N/A	144,317	265,160	506,846
Hol-Chan	10.70	112.86		45.15	N/A	182,919	336,855	644,726
Turneffe	16.80	1187.95		475.18	N/A	202,478	369,868	704,648
Punta De Manabique	44.00	464.12		116.03	N/A	142,980	259,943	493,868
Utila	18.85	75.70		27.52	N/A	173,256	318,706	609,606
Roatán	30.28	224.37		70.58	N/A	173,256	318,706	609,606
Guanaja	19.30	850.36		340.14	N/A	173,256	318,706	609,606
Cayos Cochinos	16.10	232.98		93.19	N/A	171,322	314,838	601,870
Total		3,484		1,302	0	1,511,066	2,771,888	5,293,533

Table 29: Cost of repair of all the damaged area. Cost for both phases, in USD.

Immediate and Mid-Term response Cost								
Site	Live Coral Cover %	Area with Lcc (Ha)	Loss of Projected Lcc	Area with Loss of Lcc	Intervened Area (100%)	USD Cost of response	USD Cost of response	USD Cost of response
	%	Ha	%	Ha	Ha	25%	50%	100%
Banco Chinchorro	12.30	20.06	4.92	8.02	8.02	201,073	357,244	669,587
Xcalak	17.70	315.87	7.08	126.35	126.35	455,042	863,847	1,681,456
Hol-Chan	10.70	112.86	4.28	45.15	45.15	407,093	746,073	1,424,032
Turneffe	16.80	1187.95	6.72	475.18	190.07	1,287,952	2,426,534	4,703,698
Punta De Manabique	44.00	464.12	11.00	116.03	58.01	359,184	662,359	1,268,709
Utila	18.85	75.70	6.85	27.52	11.01	271,477	485,046	912,185
Roatán	30.28	224.37	9.52	70.58	28.23	386,471	712,612	1,364,894
Guanaja	19.30	850.36	7.72	340.14	136.06	1,006,815	1,918,498	3,741,865
Cayos Cochinos	16.10	232.98	6.44	93.19	37.28	383,748	701,308	1,336,429
Total		3,484		1,302		4,758,856	8,873,522	17,102,855

Table 30: Cost of repair considering a response capacity of 3 brigades (18 divers, 12 snorkelers and 3 boats). Cost of immediate response, mid-term response and total for both phases, in USD.

Site	Live Coral Cover	Live Coral Cover area	Loss of live coral cover	Usd Cost of Intervention	Usd Cost of Intervention	Usd Cost of Intervention
	%	Ha	Ha	25%	50%	100%
Immediate response Cost						
Banco Chinchorro	12.30	20.06	8.02	91,016	156,211	286,602
Xcalak	17.70	315.87	126.35	69,474	120,242	221,778
Hol-Chan	10.70	112.86	45.15	118,295	196,967	354,313
Turneffe	16.80	1,187.95	475.18	142,125	236,664	425,742
Punta De Manabique	44.00	464.12	116.03	71,920	112,830	194,650
Utila	18.85	75.70	27.52	122,009	207,895	379,668
Roatán	30.28	224.37	70.58			
Guanaja	19.30	850.36	340.14			
Cayos Cochinos	16.10	232.98	93.19	105,557	175,526	315,464
Total		3,484	1,302	964,413	1,622,127	2,937,553
Mid-Term response Cost						
Banco Chinchorro	12.30	20.06	8.02	147,281	269,106	512,757
Xcalak	17.70	315.87	126.35	144,317	265,160	506,846
Hol-Chan	10.70	112.86	45.15	182,919	336,855	644,726
Turneffe	16.80	1,187.95	475.18	202,478	369,868	704,648
Punta De Manabique	44.00	464.12	116.03	142,980	259,943	493,868
Utila	18.85	75.70	27.52	173,256	318,706	609,606
Roatán	30.28	224.37	70.58			
Guanaja	19.30	850.36	340.14			
Cayos Cochinos	16.10	232.98	93.19	171,322	314,838	601,870
Total		3,484	1,302	1,511,066	2,771,888	5,293,533
Immediate and Mid-Term response Cost						
Banco Chinchorro	12.30	20.06	8.02	238,297	425,318	799,358
Xcalak	17.70	315.87	126.35	213,791	385,402	728,625
Hol-Chan	10.70	112.86	45.15	301,214	533,822	999,038
Turneffe	16.80	1,187.95	475.18	344,602	606,531	1,130,389
Punta De Manabique	44.00	464.12	116.03	214,900	372,773	688,518
Utila	18.85	75.70	27.52	295,265	526,602	989,274
Roatán	30.28	224.37	70.58			
Guanaja	19.30	850.36	340.14			
Cayos Cochinos	16.10	232.98	93.19	276,879	490,364	917,333
Total		3,484	1,302	2,475,480	4,394,015	8,231,085