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Assessment of Chemical Risks Associated with Hydrometeorological Phenomena in a Mexican Port on the Gulf of Mexico

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Abstract: Accidents in port areas in the Gulf of Mexico have had great economic costs, since this is an area exposed to extreme phenomena. Tropical cyclones or cold fronts, also known as Tehuantepecers, result in intense winds and waves that impact the coastal infrastructure. The chemical risk associated with extreme winds and waves for the fuel storage tanks of the facility of the Port of Veracruz, the main Mexican port in the Gulf of Mexico, was evaluated with a historical analysis of accidents as a tool to identify significant factors in disasters and establish risk acceptance criteria. It was found that the critical hazard threshold for Veracruz corresponds to winds stronger than 160 km/h (44 m/s) that may result in coastal waves of more than 5 m high. The vulnerability to these phenomena was calculated with the vulnerability index (*VI*), considering the structural, functional, and chemical factors in the infrastructure, including exposure levels. By means of a risk matrix, it was determined that gasoline storage tanks have a moderate chemical risk, since exposure to the extreme wind wave hazard is low, and diesel tanks are at low risk. These assessments are important elements to consider in the expansion plans for the Port of Veracruz.

Keywords: risk assessment; storage tanks; extreme wind; port facility; NaTech (natural–technological)

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1. Introduction

Studies on disasters or accidents with chemical substances stored in ports indicate that in vulnerable facilities, meteorological phenomena have had negative consequences in the form of a "domino effect", defined as NaTech (natural–technological) events [1–5]. Hydrometeorological phenomena affecting port facilities along the Gulf of Mexico constitute natural hazards and are mainly associated with intense winds and high waves produced by tropical cyclones or cold fronts that turn into "Nortes" over the southern part of the Gulf of Mexico [6]. This region is recognized worldwide for its important value in ecological, economic, and social terms [7,8]. Hurricanes impacting this region have resulted in chemical disasters involving large amounts of petroleum products released into the environment (for example, flammable gases and liquids) [9]. In this way, chemical accidents in ports frequently result in impacts on human health and large economic and ecological losses [2,10–12]. The most common impacts of strong winds and coastal surges correspond to the damage of fuel storage systems [12–15]. Hurricane Katrina in 2005, in Louisiana, USA, affected port facilities and produced more than 200 releases of hazardous materials into the environment [16–18].

The Port of Veracruz, in the southern part of the Gulf of Mexico, is in a process of growth that will result in the handling of larger amounts of chemical products and, consequently, larger exposure to natural hazards. The evaluation of present and future chemical risks is required in order to define risk management strategies in the port facilities. As the main Mexican port, in 2016 Veracruz handled around 23 million tons of commercial cargo [19]. The direction of the Administration of the National Port System of Veracruz ("ASIPONA-Veracruz") manages the project to expand the capacity of the port from 23 to 95 million tons of commercial cargo [20], including the installation of a new petroleum product storage terminal [21]. In 2021, the handling of 32 million tons was recorded, a fact that denotes the growth of the port [22]. Gasoline, diesel, and other chemical substances are stored within its facilities in high-capacity tanks. The factors that increase the risk of chemical accidents associated with tropical cyclones and "Nortes", such as their strong winds and accompanying storm surges, depend on the hazard of these meteorological systems, as well as on the exposure and vulnerability of the storage of chemical products of the port. The exposure is increased as the storage capacity of the port facility grows, so it is expected that the current risk will change with the expansion of the infrastructure. To define risk management strategies to prevent the occurrence of an accident, it is necessary to quantify the risk level at different times considering the changes in the port infrastructure, and estimate the costs of prevention and remediation actions.

The objective of this study was to evaluate the chemical risks for the Port of Veracruz, specifically the maritime terminal and storage service "Centro Embarcador Bajos La Gallega" of "Petróleos Mexicanos (PEMEX)", where gasoline and diesel storage tanks are exposed to extreme wind waves. This analysis may serve to guide risk assessment considerations of the new facilities to extreme weather phenomena.

2. Description of the Study Area

The Port of Veracruz, on the coast of the Gulf of Mexico, includes an artificial bay protected by breakwaters to the southeast, northeast, and northwest, and close to islands, reefs, and shallows (Figure 1) [19,23,24]. The "Centro Embarcador Bajos la Gallega" facility, belonging to PEMEX, is the largest and most important oil company in Mexico [25], where the reception, storage, and dispatch of diesel and gasoline is carried out to tankers coming from national and international points. In the study area, there are six atmospheric tanks (Figure 1): three that store regular gasoline: TV-1, TV-2, and TV-3; two that store diesel, TV-4 and TV-5; and the TV-6, which is out of service. Each one has a net storage capacity of 30,000 barrels (4769.62 m^3) and a design based on the specifications of standard 650 of the American Petroleum Institute (API) [26].

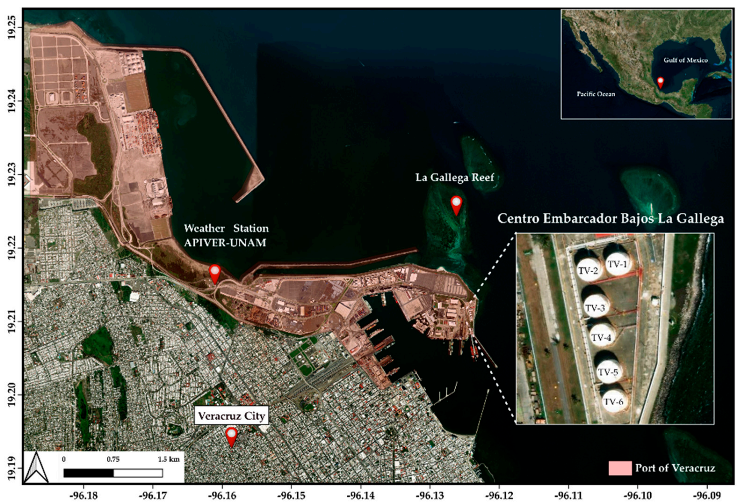

Figure 1. Location of the Port of Veracruz and "Centro Embarcador Bajos La Gallega". Own elaboration based on the QGIS program [27].

3. Methodology

To assess the risk to the petrochemical products, a hydrometeorological hazard analysis was performed using data from the weather station and wave height estimates during extreme weather events. It was considered that the hazard, related to winds and waves, resulted in damage when the risk levels surpass certain threshold levels. Historical meteorological information and records on disasters (of dates when storage tanks disasters occurred in other parts of the world) were used to estimate the critical level for the hazard. This information corresponds to that available in the year 2019, where 100 accidents in storage tanks with characteristics similar to those of the study area were analyzed, that is, vertical tanks that stored chemical substances, mainly oil and derivatives, which due to their vulnerable conditions were affected by some hydrometeorological hazard. The extreme wind wave conditions that constitute a critical hazard for the Port of Veracruz were determined (Section 3.1).

The vulnerability was calculated considering the structural, functional, and chemical characteristics of the exposed fuel storage tanks in the Port of Veracruz (Section 3.2). A risk matrix was generated integrating the hazard criteria for extreme wind and waves, and a composite index of the vulnerability of the fuel storage tanks was built with the factors mentioned above (Section 3.3).

Given the proposed expansion of the Port of Veracruz, it was possible to propose risk management measures by reducing vulnerability to the natural hazards related to "Nortes" and tropical cyclones (Section 3.4). See Figure 2.

Figure 2. Methodological scheme of risk assessment.

3.1. Identification and Characterization of Hazards

3.1.1. Historical Analysis of Accidents

The historical analysis of accidents was carried out with information available in the year 2019 for the period 1970 to 2018. It yielded information on 100 disasters evaluated internationally in storage tanks with design characteristics similar to those of the study area. Most of the references were tanks containing oil and derivatives, whose main vulnerability factor was the exposure level to extreme hydrometeorological conditions. The collected data were the bibliographic source, date, place of the event, characteristics of the tank, the substance contained, a brief description of the event, the hydrometeorological hazard and conditions, the initial accident and domino effect, as well as observations.

3.1.2. Critical Hazard

Critical hazard and risk levels were determined by combining vulnerability with meteorological and oceanographic hazard characterization, that is, relating wind speed and its waves associated with the impacts on vulnerable tanks at the time of the damage. We considered vulnerability as the characteristics and circumstances of the storage tanks that made them susceptible to the damaging effects of this hazard and the hazard as the potential occurrence of conditions generated by tropical cyclones and "Nortes".

3.1.3. Extreme Hydrometeorological Conditions in the Port of Veracruz

The wind and wave data for Veracruz came from the APIVER-UNAM weather station located inside the port and from the NOAA Wavewatch III model (WWIII), from February 2005 to May 2019 [28]. In situ wind measurements of the study area were analyzed from May 2017 to September 2019, to characterize the probabilities of winds above the critical hazard level. Additionally, information from the National Hurricane Center (NHC) [29] and the Mexican Chamber of the Construction Industry ("Cámara Mexicana de la Industria de la Construcción: CMIC") [30] was considered.

3.2. Exposed Elements and Vulnerability

NaTech disaster risk depends on the magnitude of the natural hazard and many other factors such as the degree of exposure, the type of substance, its quantity, the type of storage tank, the structural integrity of the container, its design, age, maintenance, safety management at the facility where it is located, its proximity to other tanks, etc. [31]. Therefore, the vulnerability of the fuel storage tanks of the study area was evaluated considering these structural, functional, and chemical aspects. Since there are no universally accepted norms for constructing these factors [32,33], the vulnerability index *VI* was calculated with the coastal vulnerability index equation using the variables of interest for this study, since this method allows independent variables to be qualified in a comparable way [34] as shown in the Equation (1).

$$VI = \sqrt{\frac{F1 * F2 * F3 * F4 * F5 * F6 * F7}{n}} \quad (1)$$

where: *VI* = vulnerability index, *F1* = location factor, *F2* = resistive capacity factor, *F3* = damage mechanisms factor, *F4* = preparedness and emergency response factor, *F5* = physical factor, *F6* = health factor, *F7* = environmental factor, and *n* = number of variables.

In structural vulnerability, variables that describe the physical characteristics of the tanks were integrated, through factors *F1*, *F2*, and *F3*. Functional safety elements in the installation were verified and represented by factor *F4*. Regarding chemical vulnerability, consequences that may occur due to the properties of the stored substances were considered. For its assessment, variables were chosen for their relevance in technological disasters triggered by hydrometeorological phenomena, with five categories identified: very low (1), low (2), moderate (3), high (4), and very high (5). Each variable was assigned a score from 1 to 5 and in the case of factors with multiple variables, their values were multiplied. Tables 1–3 show the variables considered. Some variables do not have five criteria to be assessed, in these cases in their place appear a hyphen, leaving only the evaluation options with information available.

The vulnerability index for each exposed element was calculated using Equation (1), where the value of *n* depended on the variables considered for each exposed element. The categories were defined by means of *VI* percentile intervals, where $VI \leq 25$ corresponded to low vulnerability, $25 > VI \leq 50$ moderate, $50 > VI \leq 75$ high, and >75 very high [35,36].

Table 1. Criteria for assessment of structural vulnerability factors.

Factor	Variable	Value Very Low 1	Low 2	Moderate 3	High 4	Very High 5
F1: Location [1]	*V1*: Elevation (m)	>30	>20 ≤30	>10 ≤20	>5 ≤10	≤5
	V2: Orientation (°)	≥225 SW <315 NW	≥135 SE <225 SW	-	≥315 NW <45 NE	≥45 NE <135 SE
	V3: Distance from the coastline (m)	>1000	>200 ≤1000	>50 ≤200	>20 ≤50	≤20
	V4: Geomorphology	Rocky, high cliffs (≥40 m)	Medium cliffs (≥20 <40 m), indented coasts	Low cliffs (≥10 <20 m), alluvial plains.	Cobble beaches, estuary, lagoons	Barrier beaches, sand beaches, saltmarsh, mudflats, deltas, coral reefs
F2: Resistive capacity [1]	*V5*: Anchorage	Anchored tank	-	-	-	Unanchored tank
	V6: Filling level (%)	≤75 >25	≤25 >15	≤15 >10	≤10 >5	≤5
	V7: Ring stiffener	With ring stiffener	-	-	-	Without ring stiffener
	V8: Density of the liquid (g/cm^3)	Water 0.997	Petroleum 0.950	Diesel 0.910	Gasoline 0.730	Solvents 0.650
	V9: Critical pressure of the vessel (Pa)	≥17,276	<17,276 ≥13,370	<13,370 ≥10,770	<10,770 ≥8159	<8159
F3: Damage mechanisms	*V10*: Corrosion	- System with intact paint	E System with almost intact paint	F System with aged paint, most of it intact	G System with heavily weathered, blistered and discolored paint, presence of small flakes, but clean	H Fully weathered, blistered, discolored and peeling paint system

[1] The result of these factors was the product of the values assigned to their variables.

Table 2. Criteria for assessment of functional vulnerability factors.

Factor	Variable	Value Very Low 1	Low 2	Moderate 3	High 4	Very High 5
F4: Preparedness and emergency response [1]	*V11*: Monitoring and control systems *V12*: Sewerage *V13*: Fire protection system	Complies with the NOM-006-ASEA-2017	-	-	-	Does not comply with the NOM-006-ASEA-2017
	V14: Hydrometeorological warning systems	Monitor and consider forecasts	-	Consider forecasts	-	Does not use them
	V15: Fire service	Fire service at the facility and mutual aid service	Fire service at the facility	Mutual aid service	Efficient communication with the fire department and the industry	Inefficient communication with fire department, no fire service or mutual aid service

[1] The result of these factors was the product of the values assigned to their variables.

Table 3. Criteria for assessment of chemical vulnerability factors.

Factor	Variable	Value				
		Very Low 1	Low 2	Moderate 3	High 4	Very High 5
F5: Physical	*V16*: Flammable liquids	Category 4	Category 3	-	Category 2	Category 1
F6: Health [1]	*V17*: Dermal-inhalation acute toxicity	Category 5	Category 4	Category 3	Category 2	Category 1
	V18: Skin corrosion/irritation	Category 3	Category 2	Category 1C	Category 1B	Category 1A
	V19: Germ cell mutagenicity	Category 2	-	Category 1B	-	Category 1A
	V20: Carcinogenicity	Category 2	-	Category 1B	-	Category 1A
	V21: Reproductive toxicity	Category 2	-	Category 1B	-	Category 1A
	V22: Specific target organ toxicity-single exposure (STOT-SE)	Category 3	-	Category 2	-	Category 1ACategory 1B
	V23: Specific target organ toxicity-repeated exposure (STOT-RE)	Category 2	-	-	-	Category 1
	V24: Aspiration hazard	Category 2	-	-	-	Category 1
F7: Environmental	*V25*: Acute aquatic toxicity	Chronic 4	Chronic 3	-	Chronic 2	Chronic 1

[1] The result of these factors was the product of the values assigned to their variables.

3.2.1. Structural Vulnerability

The location factor (*F1*) includes variables that describe the coastal characteristics of the environment, such as the elevation (*V1*) of land with respect to sea level [36–39], the orientation (*V2*) of the percentage of the perimeter without obstructions of the wind wave, the distance from the coastline (*V3*) [38,40], and geomorphology (*V4*), since wave energy is related to erosion capacity, where relief and vertical movements of the earth are considered indicators of flood risk [35,36].

Regarding the resistive capacity factor (*F2*), the design and operation variables of the fuel storage tanks were characterized. Those without anchors (*V5*) in their foundations [41,42] were considered more vulnerable. Other vulnerabilities include the filling level (*V6*) below 15% [12,15,42–49], the lack of a ring stiffener (*V7*) providing less resistance to the pressure exerted by the wind waves [42,50] and a low density of the liquid (*V8*) [47,51]. The critical pressure of the vessel (*V9*), which is the maximum resistance pressure of the material with which it is manufactured, was also considered. In this variable, the intervals selected for each vulnerability category were based on the percentiles of the critical pressure data of the tanks evaluated in the case study of Landucci et al. 2012 [47]; therefore, the percentile $\geq$95 was classified as very low, <95 to $\geq$75 low, <75 to $\geq$50 moderate, <50 to $\geq$25 high, and <25 very high. The critical pressure of the tanks evaluated in this study was calculated with Equation (2), which may have up to a 40% error in its calculation in small tanks (<5000 m^3); however, it is feasible to use it since this percentage underestimates the value of P_{cr}, which leads to an evaluation on the safe side [43,45,47,48].

$$P_{cr} = k_1\, C + k_2 \tag{2}$$

where: P_{cr} = critical pressure (Pa), $k_1 = -0.199$, $k_2 = 6950$, and C = tank capacity (m^3).

The tanks are in a coastal environment with characteristics that promote corrosion [52,53], so the corrosion (*V*10) variable in the damage mechanisms factor (*F3*) evaluated if any change had occurred since its initial physical condition [54–56]. See Table 1.

3.2.2. Functional Vulnerability

The preparedness and emergency response factor (*F4*) considered compliance with NOM-006-ASEA-2017 [57] in the variables of monitoring and control systems (*V*11), sewerage (*V*12), and the fire protection system (*V*13). In addition, hydrometeorological warning systems (*V*14) and the access to fire Services (*V*15) in the facility were verified visually and by personal communication, since two visits were made to the study area. See Table 2.

3.2.3. Chemical Vulnerability

The variables considered in the physical (*F5*), health (*F6*), and environment (*F7*) factors correspond to the criteria established in the Globally Harmonized System (GHS) of classification and labeling of chemicals [45,58]. See Table 3.

3.3. Risk Matrix

The risk matrix integrated the extreme wind hazard frequency criteria (f) and the vulnerability of the tanks considering their exposure levels.

The f included implicitly the waves due to the scarcity of their data on the site, assuming that in this place the generation of high waves is related to the intense winds. It was evaluated using the wind return periods (t_r) of 10, 50, and 100 years, since the storage tanks evaluated were designed with the API 650 standard and this design considered wind speeds for t_r of 50 years. [26]. The probability of a natural hazard can be estimated by means of the t_r using Equation (3) [43,59].

$$f = \frac{1}{t_r} \tag{3}$$

The f intervals were chosen as follows: high to $f < 0.1$ ($t_r < 10$ years), medium $0.1 \geq f < 0.02$ (10 years $\geq t_r < 50$ years), low $0.02 \geq f < 0.01$ (50 years $\geq t_r < 100$ years), and remote $f \geq 0.01$ ($t_r \geq 100$ years).

The interval of f to which the tanks of the study site are exposed corresponded to a t_r with a wind speed above a threshold of 160 km/h (44 m/s), since in the historical analysis of accidents this threshold represents a critical hazard to the structure of the tanks, owing to the fact that at this intensity it was observed that the tanks began to show impacts to a greater or lesser degree depending on their vulnerability conditions, in addition to the fact that those evaluated in this study were designed for wind speeds above 150 km/h (42 m/s).

The *VI* calculated for each of the tanks contributed by semi-quantitatively estimating the vulnerability of the tanks, through the categories obtained with the 25th, 50th, and 75th percentiles.

3.4. Management Proposals

Considering the results and that it is the evaluation of the chemical risk associated with a hazard of natural origin triggered by tropical cyclones and “Nortes” in the Port of Veracruz, the observations and management proposals focused on applicable actions for the reduction of the vulnerabilities detected on the site, which would not represent changes of reconstruction or relocation of the tanks and which have prevented accidents such as those mentioned in this study, in other ports with oil product storage tanks. The proposed actions tackled the variables with the highest scores results, so that in turn, this allows the reduction of the estimated risk.

According to the above, the proposals related to structural vulnerabilities focused on the variables of factors *F2* and *F3*. As for the functional ones, they related to those that provided greater tools to manage risk.

4. Results and Discussions

4.1. Hazard Identification and Characterization

4.1.1. Historical Analysis of Accidents

According to the historical analysis of accidents in storage tanks in the period from 1970 to 2018, the hydrometeorological hazards are: lightning (52%), wind/waves (31%), rain (9%), wind/rain affectations synergistically (1%), floods (2%), and hurricanes where the hazard associated with the accident is not specified (5%) (Figure 3). The wind and waves hazard was considered as one, owing to the first one acting as a generating force for the second one.

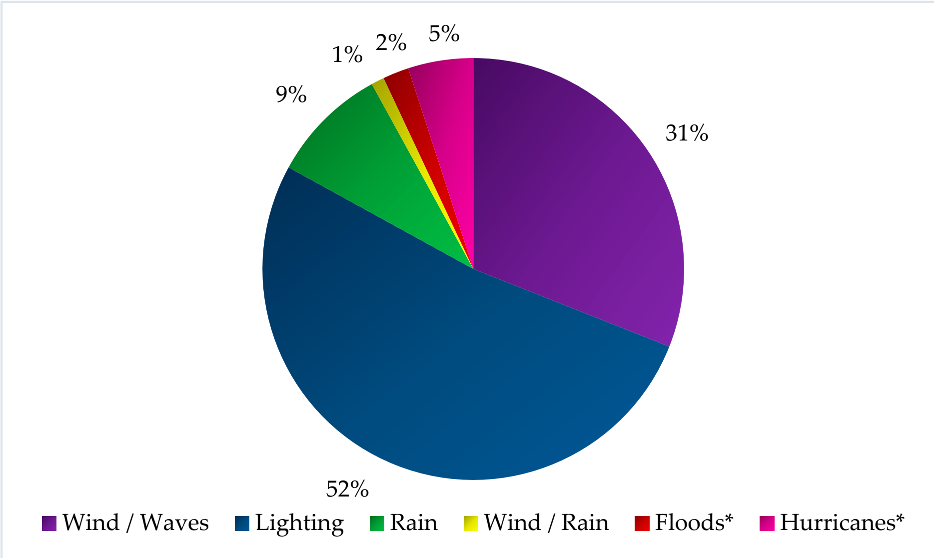

Figure 3. Hydrometeorological hazards [60]. * The hazard associated with the accident is not specified.

Regarding the accidents associated with hydrometeorological hazards, fires due to lightning strikes were mainly observed. This finding shows the importance of chemical risk assessments considering each of the hydrometeorological hazards; nevertheless, the scope of this study focuses on evaluating the effects of extreme wind and waves, whose impacts were associated with the shell insulation damage tanks and structural failures, due to intense loads of wind and wave (Figure 4). Among structural failures observed, roof damage, displacement of the tanks from their foundations, buckling due to wind pressure or impact of projectiles, overturning, collapse, or cracking stood out. In turn, structural failures resulted in chemical emergencies due to the release of stored substances in the form of spills, atmospheric emissions (toxic or flammable), and fires and/or explosions.

4.1.2. Critical Hazard

The critical hazard in fuel storage tanks was above 160 km/h (44 m/s) with serious damage at 190 km/h (53 m/s), since the impacts on the fuel storage systems were observed at this threshold (Figure 5). This is likely related to the fact that many storage tanks are designed with the API standards, which indicate design wind speeds of 190 km/h (53 m/s), wind gusts of 3 s determined by the American Society for Civil Engineers (ASCE) 7 [61], or 3 s wind gusts based on a 2% probability of annual exceedance (mean recurrence interval of 50 years) [26].

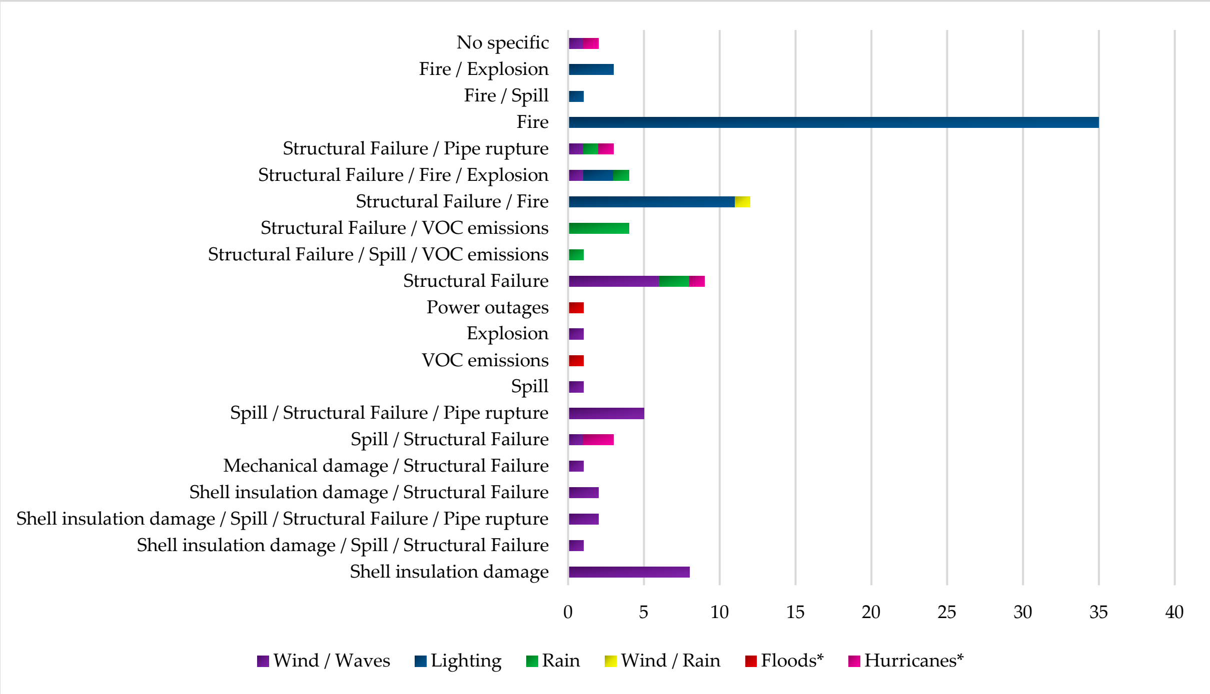

Figure 4. Accidents associated with hydrometeorological hazards [60]. * The hazard associated with the accident is not specified.

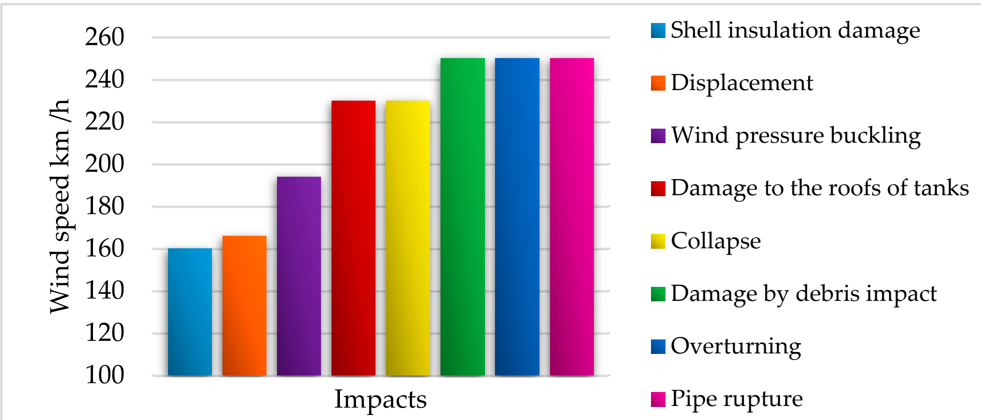

Figure 5. Impacts observed on fuel storage tanks at different wind speeds.

The severity of the impacts on the tanks depends on their vulnerability and exposure to hydrometeorological events, since in the disasters it was observed that the tanks were practically empty to less than 15% of their capacity, without anchors, or in vulnerable structural conditions [43,44,46].

4.1.3. Extreme Hydrometeorological Conditions in the Port of Veracruz

The Port of Veracruz is affected by low pressure systems such as tropical cyclones in the months of June to November, as their development is favored by the warm temperatures of the ocean surface. On the other hand, in October to May there are cold fronts generated by cyclones from mid-latitudes, which are named “Nortes” because anticyclonic winds with a northerly component prevail after their passage [6,24,62,63]. These meteorological phenomena increase the intensity of the wind, since it is a coastal area. Storm characteristics such as intensity, size, the “inverse barometer effect”, the speed of advance, and the angle of approach to the coast, in addition to geomorphology and bathymetry, cause the sea level to rise by increasing waves and storm surge [6,64–66].

The wind wave relationship in the study area is presented in Figure 6, where it is observed how the significant wave height is affected by the wind, where winds greater than 15 m/s (54 km/h) tend to induce waves equal to or greater than 2 m in height. Part of the waves are generated by offshore wind, which is why it is not a linear relationship.

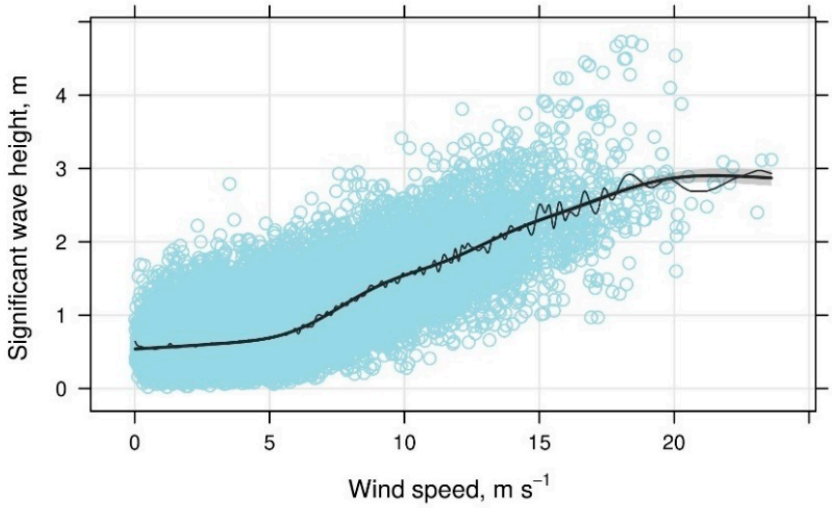

Figure 6. Wind wave relationship, with data obtained with the Wavewatch III model for the period 2005–2019. The light blue circles show the x-y data pairs, while the black lines show a spline interpolation and a smooth trend line with a 95% confidence interval.

Data from the APIVER-UNAM meteorological station from May 2017 to September 2019 indicate that the most frequent speed is 18 km/h (5 m/s) with a predominant direction from the N (Figure 7a), and that at least three times per year there can be winds greater than 100 km/h (28 m/s), due to the "Nortes" effects. The probability of higher winds is remote (0.00002) considering that the database corresponds to continuous monitoring for only two years, during which there were no representative records of tropical cyclones. On the other hand, the National Hurricane Center (NHC), has records of wind gusts of up to 152 km/h (42 m/s), due to the passage of Category 3 Hurricane Karl, in 2010 [30], and the Mexican Chamber of the Construction Industry ("Cámara Mexicana de la Industria de la Construcción: CMIC") [30] estimates that the Port of Veracruz has a probability of 0.02 for winds of 175 km/h (49 m/s).

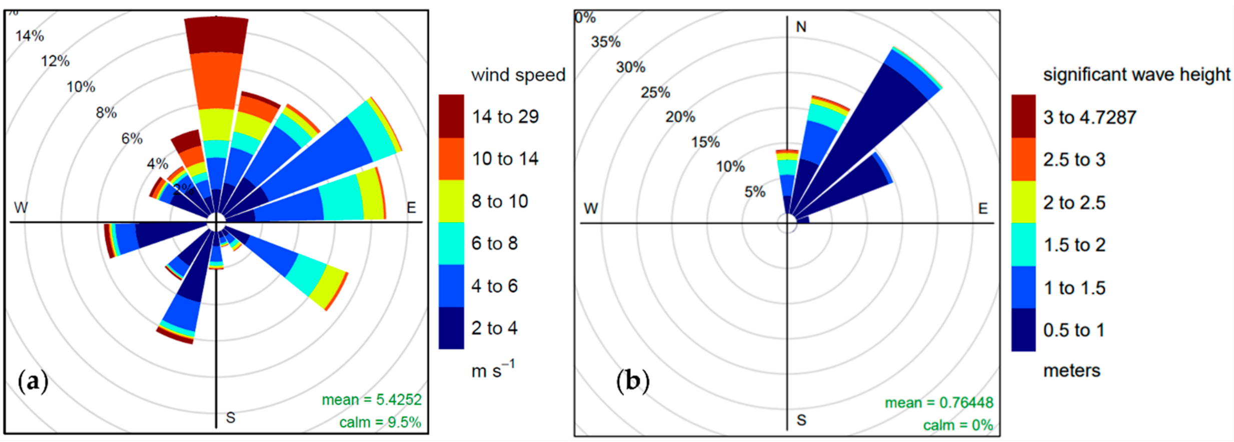

Figure 7. (**a**) Wind rose data from the APIVER-UNAM weather station May 2017 to September 2019, (**b**) wave rose data from the WWIII reanalysis period February 2005 to May 2019.

Waves are predominantly calm with significant wave heights of 0.5 to 1 m, from NE direction; however, waves greater than 4 m in height are also generated less frequently at the site (Figure 7b) [28].

4.2. Exposed Elements and Vulnerability

4.2.1. Structural Vulnerability

The location factor (*F1*) was the same for all the exposed elements owing to their being in the same place, where the variables *V1* and *V4* obtained a high and very high vulnerability, respectively, since land has an elevation of 8 to 10 m above sea level and the geomorphology of the coast corresponds to the "La Gallega" coral reef [67]. In the resistive capacity factor (*F2*), *V*6 was valued in the highest category, as it is an empty tank that is out of service. On the other hand, for the tanks that have gasoline storage, *V*8 was rated 4, since it is a low-density substance, while *V9* had a very high vulnerability, as the P_{cr} of the tanks was in the percentile interval <25 in the case study of Landucci et al. 2012 [47]. Regarding the damage mechanisms factor (*F3*), a degree of corrosion with category 4 was determined, because the coating of the tanks was strongly weathered, blistered, and discolored, with the presence of small scales.

4.2.2. Functional Vulnerability

In the preparedness and emergency response factor (*F4*), the highest variable was *V15*, since the study site kept track of the weather forecasts provided by the National Meteorological Service (SMN).

4.2.3. Chemical Vulnerability

The TV-6 tank was excluded from the chemical vulnerability assessment, since it is empty.

In the physical factor (*F5*), the TV-1, TV-2, and TV-3 tanks were highly vulnerable, since gasoline belongs to category 2 of highly flammable liquids and vapor. Likewise, in the health factor (*F6*), these tanks stood out in *V20* for containing a category 1A carcinogen, while the diesel storage tanks TV-4 and TV-5 in *V22* were classified in the category 1, as diesel causes damage to organs. On the other hand, the very high assessment of *V24* was because both fuels belong to category 1 since they may be fatal if swallowed and enter airways. In the environmental factor (*F7*), *V25* was rated 4 for the tanks with gasoline because it is a substance that may cause long-lasting harmful effects to aquatic life. In the case of diesel, there was insufficient data to classify it [58].

A summary of the values assigned to each variable considered for the calculation of the *VI* is shown in Table 4.

Three groups differentiated by the substance they store were observed. The TV-1, TV-2, and TV-3 tanks resulted in the high category (orange) with *VI* = 3698.65, and the TV-4 and TV-5 in the moderate (yellow) *VI* = 887.12, while the TV-6 was in the low (green) *VI* = 55.26. The associated vulnerability categories were calculated as the 25th, 50th, and 75th percentiles. Therefore, the gasoline tanks had a high vulnerability, while the diesel tanks and the TV-6 tank that was out of service had moderate and low vulnerability, respectively (Table 5).

It is important to highlight that the development and industrialization the Port of Veracruz will increase the exposure of oil-product storage facilities to extreme weather events, as is the case of the company "ESJ Renovable III" facility, operated by the "IENova Group". This facility is located on land reclaimed from the sea in the expansion area of the Port of Veracruz and has a Shell capacity of 2.1 million bbl and an operating capacity of 1.7 million bbl, with 12 storage tanks with capacities of 50,000, 100,000, and 175,000 bbl. In addition, the distribution of fuels in the national territory is planned, mainly by road and rail transport [21]. These facts demand the need to project chemical risk studies where the new oil product storage facility in port is integrated, to identify the pertinent preventive measures, since the risk due to fuel storage and transport is major, as the exposure to dangerous substances increases.

Table 4. Values assigned to the variables considered for the calculation of *VI*.

Vulnerability	Variable or Factor Number	Variable or Factor Name	Exposed Element					
			TV-1	TV-2	TV-3	TV-4	TV-5	TV-6
Structural	*V1*	Elevation	4	4	4	4	4	4
	V2	Orientation	2.375	2.375	2.375	2.375	2.375	2.375
	V3	Distance from the coastline	3	3	3	3	3	3
	V4	Geomorphology	5	5	5	5	5	5
	F1	Location	142.5	142.5	142.5	142.5	142.5	142.5
	V5	Anchorage	1	1	1	1	1	1
	V6	Filling level	1	1	1	1	1	5
	V7	Ring stiffener	1	1	1	1	1	1
	V8	Density of the liquid	4	4	4	3	3	-
	V9	Critical pressure of the vessel	5	5	5	5	5	5
	F2	Resistive capacity	20	20	20	15	15	25
	V10	Corrosion	4	4	4	4	4	4
	F3	Damage mechanisms	4	4	4	4	4	4
Functional	*V11*	Monitoring and control systems	1	1	1	1	1	1
	V12	Sewerage	1	1	1	1	1	1
	V13	Fire protection system	1	1	1	1	1	1
	V14	Hydrometeorological warning systems	3	3	3	3	3	3
	V15	Fire service	1	1	1	1	1	1
	F4	Preparedness and emergency response	3	3	3	3	3	3
Chemistry	*V16*	Flammable liquids	4	4	4	3	3	-
	F5	Physical	4	4	4	3	3	-
	V17	Acute toxicity	2	2	2	1.5	1.5	-
	V18	Skin corrosion/irritation	2	2	2	2	2	-
	V19	Germ cell mutagenicity [1]	3	3	3	-	-	-
	V20	Carcinogenicity	5	5	5	3	3	-
	V21	Reproductive toxicity [1]	1	1	1	-	-	-
	V22	Specific target organ toxicity-single exposure	2	2	2	5	5	-
	V23	Specific target organ toxicity–repeated exposure [1]	-	-	-	1	1	-
	V24	Aspiration hazard	5	5	5	5	5	-
	F6	Health	600	600	600	225	225	-
	V25	Acute aquatic toxicity [1]	4	4	4	-	-	-
	F7	Environment	4	4	4	-	-	-

[1] Assessment of this variable was omitted for the exposed elements with insufficient data for any of the stored substances.

Table 5. Vulnerability categories.

Category	*VI* Intervals	Tanks
Low	*VI* <679.16	TV-6 (empty)
Moderate	679.16 > *VI* ≤ 2292.89	TV-4 and TV-5 (diesel)
High	2292.89 > *VI* ≤ 3698.65	TV-1, TV-2, and TV-3 (gasoline)
Very high	*VI* > 3698.65	-

4.3. Risk Matrix

According to risk acceptance criteria, it was determined that the TV-1, TV-2, and TV-3 tanks with gasoline were at moderate chemical risk associated with extreme wind hazard, due to the intersection of the high vulnerability of the tanks and low f in the Port of Veracruz due to its exposure to winds of 175 km/h (49 m/s) with tr of 50 years [30]. With this same scheme, the TV-4 and TV-5 tanks with diesel storage are at low chemical risk associated with extreme wind hazard, and the TV-6 tank is at very low risk (Table 6).

Table 6. Risk matrix.

Extreme wind hazard	High f <0.1 (t_r < 10 years)				
	Medium $0.1 \geq f < 0.02$ (10 years $\geq t_r$ < 50 years)				
	Low $0.02 \geq f < 0.01$ (50 years $\geq t_r$ < 100 years)	TV-6	TV-4 and TV-5	TV-1, TV-2 and TV-3	
	Remote $f \geq 0.01$ ($t_r \geq$ 100 years)				
Risk categories		Low $VI \leq 25$	Moderate $25 > VI \leq 50$	High $50 > VI \leq 75$	Very high $VI > 75$
Very high					
High					
Moderate		Vulnerability of tanks (Percentiles of the vulnerability index)			
Low					
Very low					

The TV-6 tank, having the highest structural vulnerability dominated by *F2*, can represent a chemical risk scenario. An example is a disaster in Port Sulphur, Louisiana, US, where the intense wind and storm surge effects of Hurricane Katrina overcame the resistive capacity of the tank that was practically empty, causing it to hit another nearby one and collapse [42].

Although the use of return periods is in force in construction and tank design standards [26,30,57,68], it is less and less recommendable to use them for the calculation of estimates of extreme hydrometeorological conditions. This is due to the nonstationarity of the climate which presents the trends. It is therefore necessary to periodically update the estimates of extreme values [69,70].

An alternative to the above is to make estimates using percentiles, considering as extreme values, the data observed above the 90th percentile. Therefore, using data from APIVER-UNAM weather station, it is estimated that the wind critical hazard to the storage tanks evaluated is remote, since the intensity of the extreme wind (95th percentile) is above 47 km/h (13 m/s) and the probability of the maximum recorded wind (104 km/h or 29 m/s) is 0.00002. According to the proposed risk matrix, the gasoline storage tanks (TV-1, TV-2, and TV-3) are currently at low risk, and diesel (TV-4 and TV-5) and the one outside operation (TV-6) are at very low risk.

The applied methodology considers the characteristics of the tanks in the case study and is reproducible in the evaluation of tanks with gasoline and/or diesel content, located in coastal facilities and designed with the API 650 standard, adapting the criteria of the vulnerability categories of *V2* orientation (Table 1), according to the environment where the tanks are located, the orientation in which the structures provide wind obstructions and protection against intense waves will be less vulnerable.

In the case of tanks with storage of different substances, it will be necessary to reconsider the criteria of *V8* density of the liquid (Table 1), and those involved in chemical vulnerability, since they are based on the properties of the substances contained (Table 3).

4.4. Management Proposals

In the evaluation of structural vulnerability, variables that can reduce their category through some change that does not imply the redesign of the facility were identified. One of these is the *V6*, since the tank TV-6 which is empty was valued with very high vulnerability. Therefore, it is recommended one of the following actions be taken: (1) Enable the tank and put it back into operation; (2) fill the tank with water, as some plants in the United States do in extreme wind and waves forecasts [42]; or (3) dismantle it in accordance with the law. On the other hand, *V10* can reduce its category, if shorter time intervals are established in the maintenance of the coating of the tanks, because the evidence shows in a period of three years a considerable degree of corrosion.

In response to *V14*, it is recommended to: (1) Hire a service that provides in situ hydrometeorological monitoring data; or (2) install the hydrometeorological monitoring system operated by the facility of the study site. These facts emphasize the opportunity to generate representative and quality databases that assist in risk assessment.

5. Conclusions

- The Port of Veracruz is at chemical risk due to the vulnerable conditions of the fuel storage areas and the occurrence of extreme hydrometeorological phenomena ("Nortes" and tropical cyclones), which cause winds greater than 160 km/h (44 m/s). In the case of gasoline, storage tanks are at moderate chemical risk associated with extreme wind waves hazard, while diesel tanks are at low risk;
- Maintenance and preventive actions in the face of extreme wind and wave forecasts are crucial to avoid disasters. Since the tanks are built, operated, and maintained according to certain standards (API and PEMEX), it is possible to determine the critical wind wave risk using disaster information;
- Vulnerabilities detected in the facility of the study site can be reduced through actions that do not necessitate the redesign of the installation, considering the filling level, corrosion, and hydrometeorological warning systems variables.

6. Recommendations

- Execute one of the following options for the TV-6 tank that is currently out of operation in the study site: (1) be rehabilitated and put back into operation, (2) be filled with water to increase its resistive capacity, or (3) be dismantled;
- Establish shorter intervals of time in the maintenance of the tanks, since being in a saline environment for a period of 3 years, the coating is observed to be strongly weathered, blistered, and discolored;
- Implement and maintain hydrometeorological monitoring systems, such as oceanographic buoys in the Port of Veracruz, since there is currently a lack of representative and quality databases, and these would serve as tools for timely decision-making;
- Verify and, if it is necessary, update the emergency response plan for the facility of the study site;
- Improve, in a multidisciplinary way, the accident reports of facilities that store chemical products, since the current ones omit consequences and specific information when a hazard is of natural origin;
- Consider ASIPONA and the facilities responsible for fuel management in this risk study in the oil product storage facilities of the New Port of Veracruz, since increasing the exposure of chemical substances to extreme weather events increases the risk;
- Update the recommended criteria for the estimation of extreme hydrometeorological conditions, as well as the design and construction standards, since the climate presents trends, and the estimates of extreme values need to be updated periodically;
- Carry out chemical risk studies associated with hydrometeorological phenomena inherent to the handling of fuels in the stages of maritime and land transport;
- It is important that risk assessments should look at multiple factors; therefore, in addition to the events analyzed in this study, chemical risk assessments associated with lightning strikes and rain hazard should be considered, since the findings indicate impacts on oil product storage tanks triggered by these reasons.

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References

1. World Health Organization Chemical. *Releases Caused by Natural Hazard Events and Disasters*; WHO: Geneva, Switzerland, 2018.
2. World Health Organization. *Chemical Releases Associated with Cyclones*; WHO: Geneva, Switzerland, 2018.
3. Organisation for Economic Co-operation and Development. *A Workshop on NaTech Risk Management (Natural-Hazard Triggered Technological Accidents)*; OECD: Paris, France, 2011.
4. Vetere Arellano, A.L.; Cruz, A.M.; Nordvik, J.-P.; Pisano, F. *Analysis of Natech (Natural Hazard Triggering Technological Disasters) Disaster Management*; Publications Office of the European Union: Ispra, Italy, 2004.
5. Zeng, T.; Chen, G.; Reniers, G.; Yang, Y. Methodology for Quantitative Risk Analysis of Domino Effects Triggered by Flood. *Process Saf. Environ. Prot.* **2021**, *147*, 866–877. [CrossRef]
6. Pérez, E.P.; Magaña, V.; Caetano, E.; Kusunoki, S. Cold Surge Activity over the Gulf of Mexico in a Warmer Climate. *Front Earth Sci.* **2014**, *2*, 19. [CrossRef]
7. National Oceanic and Atmospheric Administration. Gulf Of Mexico Region. Available online: https://ecowatch.noaa.gov/regions/gulf-of-mexico#:~{}:text=The%20Gulf%20of%20Mexico%20supports,economic%20engine%20for%20the%20region (accessed on 11 April 2022).
8. Environmental Protection Agency. Why Is It Important to Protect the Gulf of Mexico? Available online: https://www.epa.gov/gulfofmexico/why-it-important-protect-gulf-mexico#:~{}:text=Encompassing%20over%20five%20million%20acres,and%20sport%20and%20commercial%20fisheries (accessed on 11 April 2022).
9. Ricci, F.; Casson Moreno, V.; Cozzani, V. A Comprehensive Analysis of the Occurrence of Natech Events in the Process Industry. *Process Saf. Environ. Prot.* **2021**, *147*, 703–713. [CrossRef]
10. Ndimele, P.E.; Saba, A.O.; Ojo, D.O.; Ndimele, C.C.; Anetekhai, M.A.; Erondu, E.S. Remediation of Crude Oil Spillage. In *The Political Ecology of Oil and Gas Activities in the Nigerian Aquatic Ecosystem*; Elsevier: Lagos, Nigeria, 2018; pp. 369–384. [CrossRef]
11. Erickson, T.B.; Brooks, J.; Nilles, E.J.; Pham, P.N.; Vinck, P. Environmental Health Effects Attributed to Toxic and Infectious Agents Following Hurricanes, Cyclones, Flash Floods and Major Hydrometeorological Events. *J. Toxicol. Environ. Health Part B* **2019**, *22*, 157–171. [CrossRef] [PubMed]

12. Necci, A.; Girgin, S.; Krausmann, E. *Understanding Natech Risk Due to Storms*; Publications Office of the European Union: Luxembourg, 2018.
13. Girgin, S.; Krausmann, E. Historical Analysis of U.S. Onshore Hazardous Liquid Pipeline Accidents Triggered by Natural Hazards. *J. Loss Prev. Process Ind.* **2016**, *40*, 578–590. [CrossRef]
14. Sengul, H. *Hazard Characterization of Joint Natural and Technological Disasters (Natechs) in the United States Using Federal Databases*; Tulane University: New Orleans, LA, USA, 2005.
15. Huang, M.; Chen, G.; Yang, P.; Hu, K.; Zhou, L.; Men, J.; Zhao, J. Multi-Hazard Coupling Vulnerability Analysis for Buckling Failure of Vertical Storage Tank: Floods and Hurricanes. *Process Saf. Environ. Prot.* **2022**, *161*, 528–541. [CrossRef]
16. Santella, N.; Steinberg, L.J.; Sengul, H. Petroleum and Hazardous Material Releases from Industrial Facilities Associated with Hurricane Katrina. *Risk Anal.* **2010**, *30*, 635–649. [CrossRef]
17. Cruz, A.M.; Krausmann, E. Hazardous-Materials Releases from Offshore Oil and Gas Facilities and Emergency Response Following Hurricanes Katrina and Rita. *J. Loss Prev. Process Ind.* **2009**, *22*, 59–65. [CrossRef]
18. Bravo Álvarez, H.; Sosa Echeverría, R.; Sánchez Álvarez, P.; Butron Silva, A. Riesgo Químico Asociado a Fenómenos Hidrometeorológicos En El Estado De Veracruz. In *Inundaciones 2005 En El Estado De Veracruz*; Universidad Veracruzana: Veracruz, Mexico, 2006; pp. 315–326.
19. Administración Portuaria Integral de Veracruz. *Programa Maestro de Desarrollo Portuario de Veracruz 2016–2021*; APIVER: Veracruz, Mexico, 2017.
20. ASIPONA Veracruz. Nuevo Puerto de Veracruz. Available online: https://www.puertodeveracruz.com.mx/wordpress/nuevo-puerto-de-veracruz/ (accessed on 19 September 2022).
21. Salgado Álvarez, N.T. *MIA 30VE2017X0199 Terminal de Petrolíferos Veracruz*; GPPA: Cancun, Mexico, 2017.
22. ASIPONA Veracruz. Movimiento Histórico del Puerto de Veracruz. Available online: https://www.puertodeveracruz.com.mx/wordpress/blog/movimiento-historico-del-puerto-de-veracruz/#:~{}:text=La%20Administraci%C3%B3n%20del%20Sistema%20Portuario,Veracruz%20bajo%20esta%20nueva%20administraci%C3%B3n (accessed on 13 October 2022).
23. Administración Portuaria Integral de Veracruz. *Programa Maestro de Desarrollo Portuario de Veracruz 2011–2016*; APIVER: Veracruz, Mexico, 2013.
24. SEMAR. Secretaría de Marina, Veracruz. Available online: https://digaohm.semar.gob.mx/cuestionarios/cnarioVeracruz.pdf (accessed on 12 October 2022).
25. PEMEX. Petróleos Mexicanos Petróleos Mexicanos. Available online: https://www.pemex.com/Paginas/default.aspx (accessed on 3 October 2021).
26. *API 650*; Welded Steel Tanks for Oil Storage. American Petroleum Institute: Washington, DC, USA, 2012.
27. Sutton, T. Bing Aerial Map QGIS. Available online: https://docs.qgis.org/2.14/es/docs/gentle_gis_introduction/authors_and_contributors.html (accessed on 13 October 2022).
28. Environmental Modeling Center NOAA. Wavewatch III. Available online: https://polar.ncep.noaa.gov/waves/wavewatch/ (accessed on 3 October 2021).
29. Steward, S.R. *Tropical Cyclone Report*; NHC NOAA: Miami, FL, USA, 2011.
30. Cámara Mexicana de la Industria de la Construcción. *V4–TOMO III Diseño Por Viento: Normas y Especificaciones Para Estudios, Proyectos, Construcciones e Instalaciones*; CMIC: Mexico City, Mexico, 2015.
31. Cruz, A.M. Challenges in Natech Risk Reduction. *Rev. Ing.* **2012**, *37*, 79–86. [CrossRef]
32. Tate, E. Social Vulnerability Indices: A Comparative Assessment Using Uncertainty and Sensitivity Analysis. *Nat. Hazards* **2012**, *63*, 325–347. [CrossRef]
33. Neri, C.; Magaña, V. Estimation of Vulnerability and Risk to Meteorological Drought in Mexico. *Weather. Clim. Soc.* **2016**, *8*, 95–110. [CrossRef]
34. Hammar-Klose, E.S.; Thieler, R.E. Coastal Vulnerability to Sea-Level Rise: A Preliminary Database for the U.S. Atlantic, Pacific and Gulf of Mexico Coasts. Available online: https://pubs.usgs.gov/dds/dds68/htmldocs/project.htm (accessed on 3 October 2021).
35. Pantusa, D.; D'Alessandro, F.; Riefolo, L.; Principato, F.; Tomasicchio, G.R. Application of a Coastal Vulnerability Index. A Case Study along the Apulian Coastline, Italy. *Water* **2018**, *10*, 1218. [CrossRef]
36. Koroglu, A.; Ranasinghe, R.; Jiménez, J.A.; Dastgheib, A. Comparison of Coastal Vulnerability Index Applications for Barcelona Province. *Ocean Coast Manag.* **2019**, *178*, 104799. [CrossRef]
37. McLaughlin, S.; Cooper, J.A.G. A Multi-Scale Coastal Vulnerability Index: A Tool for Coastal Managers? *Environ. Hazards* **2010**, *9*, 233–248. [CrossRef]
38. Coelho, C. Riscos de Exposição de Frentes Urbanas Para Diferentes Intervenções de Defesa Costeira. Ph.D. Thesis, University of Aveiro, Aveiro, Portugal, 2005.
39. Gornitz, V. Global Coastal Hazards from Future Sea Level Rise. *Glob. Planet Change* **1991**, *3*, 379–398. [CrossRef]
40. Godoy, L.A.; Portela, G.; Sosa, E.M.; Suarez, L.E.; Virella, J.C.; Zapata, R. Damage Due to Buckling in Aboveground Storage Tanks. Proceedings of the International Conference on the Behavior of Structures with Damage, University of Puerto Rico, Mayaguez, Puerto Rico. 2002. Available online: https://www.academia.edu/47668976/Damage_due_to_buckling_in_aboveground_storage_tanks (accessed on 17 August 2022).
41. Bernier, C.; Padgett, J.E. Fragility and Risk Assessment of Aboveground Storage Tanks Subjected to Concurrent Surge, Wave, and Wind Loads. *Reliab. Eng. Syst. Saf.* **2019**, *191*, 106571. [CrossRef]

42. Godoy, L.A. Performance of Storage Tanks in Oil Facilities Damaged by Hurricanes Katrina and Rita. *J. Perform. Constr. Facil.* **2007**, *21*, 441–449. [CrossRef]
43. Ramírez Olivar, O.J.; Zuluaga Mayorga, S.; Muñoz Giraldo, F.; Sánchez Silva, M.; Pinelli, J.P.; Salzano, E. The Effects of Extreme Winds on Atmospheric Storage Tanks. *Reliab. Eng. Syst. Saf.* **2020**, *195*, 106686. [CrossRef]
44. Ramirez, O.; Mesa, A.; Zuluaga, S.; Munoz, F.; Sanchez Silva, M.; Salzano, E. Fragility Curves of Storage Tanks Impacted by Strong Winds. *Chem. Eng. Trans.* **2019**, *77*, 91–96. [CrossRef]
45. Antonioni, G.; Landucci, G.; Necci, A.; Gheorghiu, D.; Cozzani, V. Quantitative Assessment of Risk Due to NaTech Scenarios Caused by Floods. *Reliab. Eng. Syst. Saf.* **2015**, *142*, 334–345. [CrossRef]
46. Zhao, Y.; Lin, Y. Buckling of Cylindrical Open-Topped Steel Tanks under Wind Load. *Thin-Walled Struct.* **2014**, *79*, 83–94. [CrossRef]
47. Landucci, G.; Antonioni, G.; Tugnoli, A.; Cozzani, V. Release of Hazardous Substances in Flood Events: Damage Model for Atmospheric Storage Tanks. *Reliab. Eng. Syst. Saf.* **2012**, *106*, 200–216. [CrossRef]
48. Landucci, G.; Necci, A.; Tugnoli, A.; Antonioni, G.; Cozzani, V. NaTech Scenarios Caused by Flooding: Evaluation of Accident Frequency by the Use of Fragility Models. *Chem. Eng. Trans.* **2014**, *36*, 427–432. [CrossRef]
49. Analyse Recherche et Information sur les Accidents. Natech and Climate Risks Archives. Available online: https://www.aria.developpement-durable.gouv.fr/accidentologie/natech-and-climate-risks/?lang=en (accessed on 3 October 2021).
50. Aileni, K.; Prasanna, P.; Jain, P.C. Buckling Analysis of Ring Stiffened Circular Cylinders Using ANSYS. *Int. J. Res. Appl. Sci. Eng. Technol.* **2017**, *5*, 2287–2296.
51. National Oceanic and Atmospheric Administration; Environmental Protection Agency. *CAMEO Chemicals Software*; EPA: Washington, DC, USA, 2018.
52. Petróleos Mexicanos. *NRF-053-PEMEX-2005, Sistemas de Protección Anticorrosiva a Base de Recubrimientos Para Instalaciones Superficiales*; PEMEX: Mexico City, Mexico, 2006.
53. Association for Materials Protection and Performance. *SSPC-Vis 4, Guide and Reference Photographs for Steel Surfaces Prepare by Waterjetting, NACE-Vis 7*; The Society for Protecting Coatings and NACE International: Houston, TX, USA, 2001; ISBN 1-889060-56-9.
54. *API-RP-571*; Damage Mechanisims Affecting Fixed Equipment in the Refining Industry. American Petroleum Institute: Washington, DC, USA, 2003.
55. *API 653*; Inspección, Reparación, Alteración, y Reconstrucción de Tanques. American Petroleum Institute: Washington, DC, USA, 2005.
56. Al-Mitin, A.W.; Sardesai, V.; Al-Harbi, B.; Murthy, S.H.; Hannan, A.S.A. Risk Based Inspection (RBI) of Aboveground Storage Tanks to Improve Asset Integrity. In Proceedings of the Society of Petroleum Engineers International Petroleum Technology Conference, Bangkok, Thailand, 15–17 November 2011; pp. 750–755. [CrossRef]
57. *NOM-006-ASEA-2017*; Especificaciones y Criterios Técnicos de Seguridad Industrial, Seguridad Operativa y Protección al Medio Ambiente Para El Diseño, Construcción, Pre-Arranque, Operación, Mantenimiento, Cierre y Desmantelamiento de Las Instalaciones Terrestres de Almacenamiento de Petrolíferos y Petróleo, Excepto Para Gas Licuado de Petróleo. DOF: Mexico City, Mexico, 2018.
58. United Nations. *Globally Harmonized System of Classification and Labelling of Chemicals (GHS)*, 8th ed.; UN: New York, NY, USA, 2019; ISBN 978-92-1-117199-0.
59. Lee, J.K.; Lee, K.H.; Kim, S.; Yook, D.; Ahn, S. Weibull Parameter Calculation and Estimation of Wind Speeds for the Return Period: A Case Study in the Kori and Wolsong NPP Areas. *Ann. Nucl. Energy* **2017**, *108*, 406–412. [CrossRef]
60. Lara Carvajal, G.I. *Riesgos Químicos Por Manejo de Combustibles Asociados a Fenómenos Hidrometeorológicos En El Recinto Portuario de Veracruz*; Universidad Nacional Autónoma de México: Mexico City, Mexico, 2020.
61. American Society of Civil Engineers. *ASCE 7, Minimum Design Loads for Buildings and Other Structures*; American Society of Civil Engineers: Reston, VA, USA, 2003.
62. Secretaría de Protección Civil de Veracruz. *Calendario de Temporadas y Fenómenos Hidrometeorológicos Para El Estado de Veracruz*; Secretaría de Protección Civil de Veracruz: Veracruz, Mexico, 2017.
63. Magaña, V. *Los Impactos de El Niño En México*; UNAM, CONACyT e IAI: Mexico City, Mexico, 1999.
64. New Zealand Government. *Coastal Hazards and Climate Change. A Guidance Manual for Local Government in New Zealand*, 2nd ed.; Ministry for the Environment Manatu Mo Te Taiao: Wellington, New Zealand, 2008.
65. National Hurricane Center. *Introduction to Storm Surge*; NHC: Miami, FL, USA, 2012.
66. Marchand, M. *Modelling Coastal Vulnerability*; IOS Press BV: Amsterdam, The Netherlands, 2009; ISBN 978-1-60750-069-8.
67. Ortiz-Lozano, L.; Valadez, V.; Hayasaka-Ramírez, S. *Influencia Histórica de La Ciudad y Puerto de Veracruz Sobre El Sistema Arrecifal Veracruzano*, 1st ed.; Granados-Barba, A., Ortiz-Lozano, L.D., Salas-Monreal, D., González-Gándara, C., Eds.; Universidad Autónoma de Campeche: Campeche, Mexico, 2015; ISBN 978-607-8444-11-3.
68. US Army Corps of Engineers. *EM 1110-2-1100: Coastal Engineering Manual–Part II*; USACE: Washington, DC, USA, 2015.

69. Organización Mundial Meteorológica. Comunicado No. 997–Los Científicos Instan a Que Se Actualicen Con Más Frecuencia Los Períodos de Referencia Climáticos de 30 Años Para Ir a La Par Con La Rápida Evolución Del Cambio Climático. Available online: https://public.wmo.int/es/media/press-release/no-997-%E2%80%93-los-cient%C3%ADficos-instan-que-se-actualicen-con-m%C3%A1s-frecuencia-los (accessed on 3 October 2021).
70. Young, I.R.; Vinoth, J.; Zieger, S.; Babanin, A.V. Investigation of Trends in Extreme Value Wave Height and Wind Speed. *J. Geophys. Res. Oceans* **2012**, *117*, 1–13. [CrossRef]