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Investigation of mitigation strategies to reduce storm surge impacts associated with oil infrastructures

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Abstract: This paper evaluates different mitigation strategies to reduce the risks posed by aboveground storage tanks and the vulnerability of nearby communities. A framework integrating natural hazard exposure, structural vulnerability, and social vulnerability is proposed to investigate the effects and the viability of different mitigation strategies.

1 Introduction

Failures of critical oil infrastructures, such as aboveground storage tanks (ASTs), have caused severe economic and environmental impacts during recent hurricane events in the United States (US). More than 26.5 million liters of chemicals were spilled due to failures of ASTs during Hurricanes Katrina and Rita [9]. Moreover, AST failures can have significant effects on the wellbeing of surrounding communities. The Murphy Oil Spill during Hurricane Katrina forced the relocation of 1,700 homes due to the failure of a single AST [7]. Since more than 50% of the US refining capacity is located in a hurricane prone area (the Gulf Coast), it is critical to mitigate the risks associated with these infrastructures during storm surge events.

While many studies have recently proposed measures to reduce the vulnerability of ASTs [10, 11, 14, 17] during storm surge events, there is little information about the effectiveness, viability, and impacts of such measures on large portfolios of ASTs in industrial areas. Furthermore, probabilistic analysis of the effectiveness of mitigation strategies is needed given the significant sources of uncertainties associated with AST performance and spill risks. Such data is crucial for industry managers and policymakers to make risk-informed decisions to improve the resilience of the oil industry and of nearby communities. Therefore, the objective of this paper is to explore mitigation strategies for portfolios of tanks in surge prone areas. The Houston Ship Channel (HSC) is used as a case study. The HSC is the second largest petrochemical complex in the world with ten major refineries and more than 4,500 ASTs, and it is located in a hurricane prone area. First, a framework is proposed to efficiently evaluate the effects and viability of mitigation strategies. This framework couples storm surge modeling with fragility modeling of ASTs to estimate the risk of chemical spills. These results are then merged with relevant factors of social vulnerability to determine the overall vulnerability of communities located along the HSC. Next, using this model, three main types of mitigation strategies are compared: procedural measures, structural details of ASTs, and regional surge protection systems. The comparison is performed by quantifying the reduction of the spill risk, the reduction of economic impacts, the cost-benefit ratio, and the effects on communities' vulnerability. Finally, policy-oriented solutions regarding the oil industry and nearby communities are discussed.

2 Methodology

The framework used to evaluate mitigation strategies relies on the multi-disciplinary integrated model presented in Figure 1. This model was initially develop to study the evolution of risks along the HSC; further details can be found in [4]. The next sections will provide details on how this model is adapted to evaluate the effectiveness of mitigation strategies to improve storm surge resiliency.

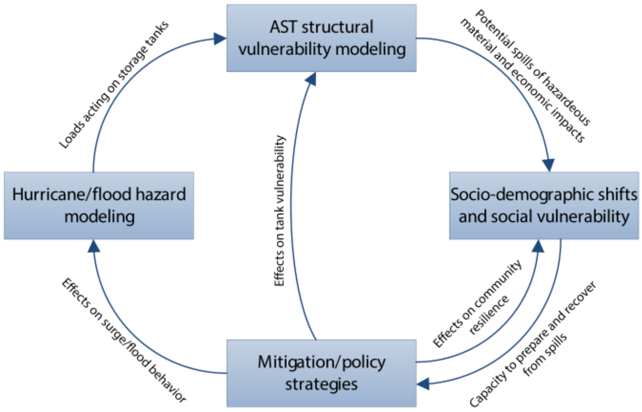

Figure 1: Overview of the integrated model to evaluate mitigation strategies (adapted from [4])

Since storm surge is usually responsible for most major AST spills during hurricane events [16], it is the only load considered here. The surge levels in the HSC are determined from the preliminary Federal Emergency Management Agency (FEMA) Base Flood Elevation (BFE) for an annual probability of occurrence of 0.2% [8]. The floodplain is presented in Figure 2, and the surge levels vary between 6.1 and 7.0 m. Mitigation strategies that affect the surge behaviour in the HSC will require additional storm surge modeling and are detailed further below.

2.1 Structural vulnerability of ASTs to surge and impacts of failures

The structural vulnerability of ASTs is assessed by using parameterized fragility functions. Fragility functions indicate the probability of failure of a structure for a given hazard level and set of structural characteristics. Post-hurricane investigations [9] have shown that failures of ASTs occur due to flotation when the uplift force from the surge is greater than the self-weight of the tank and any anchorage, and due to shell buckling when the lateral surge pressure becomes excessive. The fragility models proposed by [10] are used here. As shown in (1), they are based on a logistic regression model and are parameterized on the tank height (*H*), diameter (*D*), internal liquid height (*L*), internal liquid density (ρ_L), external surge level (*S*), steel design stress (S_d), and an additional set of parameters, given further below, $\boldsymbol{X}$ if the tank is anchored.

$$P(\text{Failure}|D,H,L,\rho_L,S,S_d,\boldsymbol{X}) = \frac{1}{1+exp\big(-l(D,H,L,\rho_L,S,S_d,\boldsymbol{X})\big)} \tag{1}$$

In this equation, $l(\cdot)$ is a logit function that is different for unanchored and anchored tanks; the logit functions can be found in [10]. The fragility models were developed by considering both failure modes using a series system assumption. The database developed in [4] is used to obtain the coordinates, height, diameter, bare earth elevation, berm elevation (*B*), and potential content of all tanks located in the HSC in 2014. Since it is a common design practice in the Gulf Coast region, all ASTs are assumed to be unanchored and, S_d is fixed at 160 MPa corresponding to the most commonly used steel grade.

Knowing the properties (*D, H, B,* $\boldsymbol{X}$) and surge exposure (S) of a tank, the probability of failure and the expected spill volume (SV) are obtained from (2) and (3). In these equations, L and ρ_L are defined as uniform random variables due to the uncertainty of these parameters prior to a hurricane. The lower and upper bounds of $f_L(l)$, the probability density function of L, are 0 and 0.9H, while the bounds of $f_{\rho_L}(\rho_l)$ are a function of the potential content of the tank. If the surge level at a given AST is lower than the berm elevation, the model reflects that S = 0.

$$P(\text{Failure}|D,H,S,S_d,\boldsymbol{X}) = \int_L \int_{\rho_L} P(\text{Failure}|D,H,L,\rho_L,S,S_d,\boldsymbol{X}) f_L(l) f_{\rho_L}(\rho_l)\, \text{d}L\text{d}\rho_L \quad (2)$$

$$E(\text{SV}|D,H,S,S_d,\boldsymbol{X}) = \int_L \int_{\rho_L} \left(\frac{\pi L D^2}{4}\right) P(\text{Failure}|D,H,L,\rho_L,S,S_d,\boldsymbol{X}) f_L(l) f_{\rho_L}(\rho_l)\, \text{d}L\text{d}\rho_L \quad (3)$$

A probability of failure map, as shown in Figure 2, is obtained by using (2) for all ASTs located in the HSC. The map shows the baseline condition where no mitigation strategy is implemented, and the total volume of storm-induced spills. Spill volume is used here as a proxy for the risks associated with ASTs. Moreover, since the failure of a single tank can have significant impacts, the number of highly vulnerable tanks (P_F > 0.75) is also used as a measure of risk. With these results, potential clean-up and repair costs are also estimated. Repair costs of ASTs are obtained from [12], while the clean-up cost is assumed to be of $12/L. This estimate is obtained from the amount spent by the US Coast Guard and the EPA during Hurricanes Katrina and Rita [19] and it represents a lower bound since it neglects the private sector and indirect costs.

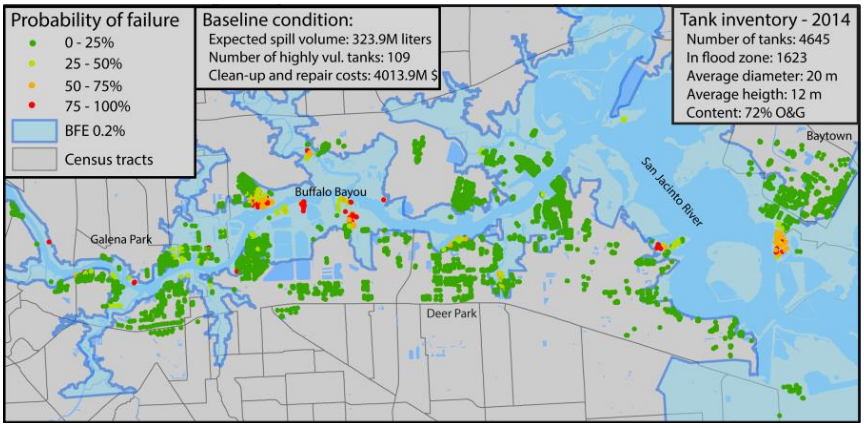

Figure 2: Probability of failure of ASTs for the baseline condition

For each mitigation strategy, the above procedure is repeated by modifying the fragility model or the surge exposure accordingly. Thus, this enables the estimation of the reduction of risks and of associated economic costs compared to the baseline condition. Moreover, the cost of implementing each strategy is estimated from [15], providing a ratio of cost-benefits.

2.2 Intersection of spill risks and social vulnerability

To investigate the intersection of spill risks and social vulnerability, the approach proposed in [6] is adopted and modified to the context of this study. As shown in Figure 3, this approach couples the spill risks with social vulnerability to determine the place vulnerability (PV) of the 21 census tracts where ASTs are located; 83,500 residents live in these tracts. Census tracts commonly serve as proxies for neighbourhoods. Social vulnerability indicates the capacity of communities to prepare, respond and recover from hazards, while place vulnerability highlights the fact that disasters emerge through interactions between the built environment and the social system [6]. From results in [4], the index of concentrated disadvantage is used as a proxy for the social vulnerability of communities along the HSC. This index globally expresses the socioeconomic status, education level, unemployment level, and household composition within a tract. The three levels of social vulnerability presented in Figure 3 were defined as the mean plus or minus one-half the standard deviation of the index of concentrated disadvantage [6]. The mean and standard deviation of the index were computed from the 1,072 tracts composing the Houston metropolitan area. The four levels of spill risks were obtained from the analysis of spills in past hurricanes [16, 19]. As detailed in Figure 3, a score is assigned for each level of social vulnerability and level of spill risk. For each tract, the product of both scores quantifies place vulnerability. The higher the product, the higher place vulnerability is considered to be. Finally, the sum for all 21 tracts with ASTs provides an overall index of place vulnerability within the HSC. Since mitigation strategies can reduce the risk of spills, this approach will allow quantification of the benefits of each strategy on the vulnerability of communities.

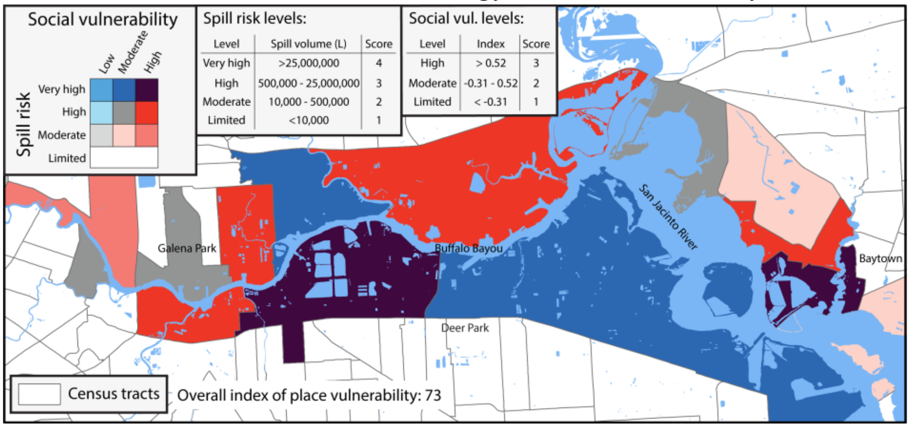

Figure 3: Bivariate map indicating place vulnerability along the HSC for the baseline condition

3 Mitigation strategies

With the methodology presented above, it is now possible to evaluate the effectiveness and viability of mitigation strategies. The effects of each strategy will first be investigated on a typical AST and then for the whole portfolio of tanks along the HSC. The case study AST has a height of 12 m and a diameter of 20 m and is filled with oil and gas products (ρ_L between 700 and 950 kg/m^3). These dimensions correspond to median values from the HSC inventory [4].

3.1 Procedural strategies

Pre-hurricane preparation guides [14] usually recommend that ASTs be emptied and filled with sea water before a storm event. If emptying the tank is not possible, the internal liquid height (L) should be at least 3 to 6 feet higher than the expected surge level. The effects of such procedures are shown in Figure 4(a) for the case study AST. This figure shows that an AST with a low internal liquid height compared to the surge level is highly vulnerable. Increasing the liquid greatly reduces fragility, but for high surge levels, the probability of failure is still significant. For tanks filled with sea water, the probability of failure is low for the whole range of surge levels. Moreover, in this case, if a spill occurs, no hazardous material is released. As shown in Table 1, similar results were obtained at the portfolio level. Filling the tanks with 6 ft of product above the surge level has a limited impact on the reduction of risk. This is due to the inefficiency of this procedure for ASTs subjected to high surge level or filled with light liquids. However, completely filling ASTs with product or water reduces the risk of spills, associated economic costs, and place vulnerability at very low levels. Finally, implementing such procedural strategies may not be feasible, and they have not always been carried out in advance of past storms. It may not be possible to empty or fill a large number of ASTs on short notice prior to a storm event. The costs associated with such procedures could not be estimated here. Nonetheless, these costs are expected to be considerably lower than the other strategies presented below.

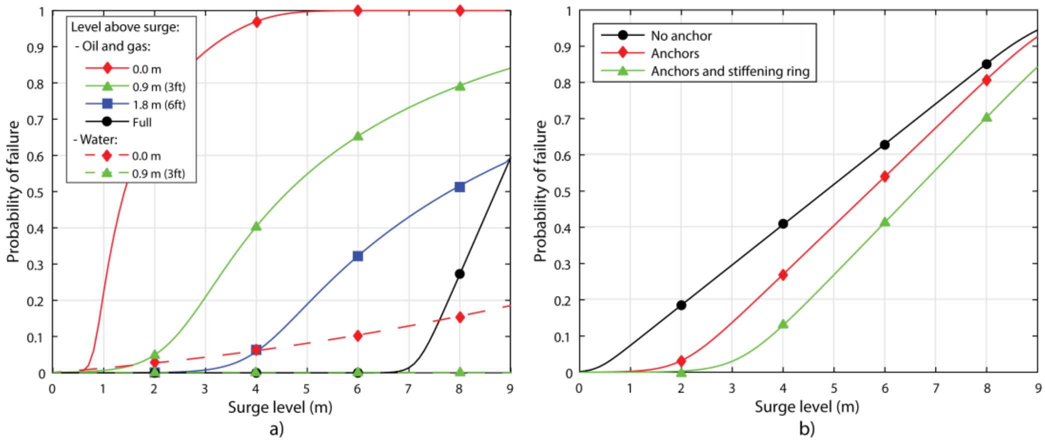

Figure 4 Fragility curves of typical AST for different: (a) internal liquid heights; (b) structural details

3.2 Structural details of aboveground storage tanks

Structural details consist of modifying the design of ASTs to prevent flotation or increase the buckling strength. Since they do not rely on human actions prior to an event and are permanent modifications of the ASTs, they are more dependable than procedural strategies.

3.2.1 Anchors

Design codes [1, 2] prescribe anchors to prevent overturning of ASTs under wind and earthquake loads. However, there are no mandatory provisions to anchor ASTs for other critical loads such as flooding; the use of anchors is left to the discretion of the owner. Moreover, in the Gulf Coast region, ASTs are typically proportionated to avoid anchorage for economic reasons. To investigate the effects of anchoring tanks, the fragility model developed by [10] is used. The fragility model considers the anchor yielding strength and the concrete cone failure strength. The additional set of parameters $\boldsymbol{X}$ in (1) corresponds to the steel strength f_y, the concrete strength f'_c, the embedment depth h_{ef}, the edge distance c, the anchor diameter d, the number of anchors n_a, and the spacing s. Anchors are designed for all ASTs located in the flood zone using load combinations for flood in [3] and the provisions in [2] for wind loads; f_y and f'_c are fixed to 400 MPa and 30 MPa respectively, and the other parameters are determined from the uplift forces acting on the tank. While the parameters are fixed for the design of anchors, their uncertainty is still propagated in the fragility model. The effect of anchorage is shown in Figure 4(b) for the case study tank (d = 25.4 mm, h = 300 mm, c = 100 mm, and s = 1 m). Using anchors reduces the probability of failure for the whole range of surge levels. However, this reduction is limited; while anchors prevent flotation, the tank now becomes more vulnerable to buckling. At the portfolio level, results from Table 1 show that anchorage is less efficient than the previous procedural methods. Nonetheless, anchorage is a cost-effective method to reduce spill risks and cleaning costs. In fact, the reduction of repair and clean-up cost is almost six times the costs of providing anchors to ASTs in the flood zone ($375 million). This highlights the economic viability of this strategy. The cost of anchoring tanks to the ground was obtained from [15] and includes foundations adequate to resist uplift forces. The average cost per tank is approximately $150,000 which represents 30% of the average cost of an AST; the average cost of an AST in the HSC is $500,000 [12].

3.2.2 Stiffening rings

Stiffening rings are commonly used on the top shell course of ASTs to prevent wind buckling. Similarly, stiffening rings can be used to prevent surge buckling of anchored tanks. The use of stiffening ring to prevent surge buckling was investigated by [11]. This study provided equations for the optimal ring location (R_h) and the critical surge height. From these equations, a fragility model for ASTs with anchors and stiffening rings is obtained from the procedure outlined in [10]. A logistic regression model of the same form as (1) is derived; however, the logit function has R_h as an additional parameter. The derived fragility model yields an accuracy of 95.7% on test data. As shown in Figure 4(b), the use of stiffening rings further reduces the fragility of the case study AST. Higher surge heights are now required to initiate buckling. As expected, providing all anchored ASTs in the HSC with stiffening rings also further decreases the risk of spills. The additional cost to provide stiffening rings to all anchored ASTs is only $18 million; the average cost per tank is $7,000. With a higher cost-benefits ratio, the use of stiffening rings and anchors is more beneficial than the use of anchors alone.

3.3 Hazard protection system

The last type of mitigation strategy investigated consists of directly reducing the surge hazard in the HSC. The protection system adopted for this study is the Mid Bay Strategy (MBS) proposed in [18] and detailed in Figure 5. Since the MBS modifies the surge behaviour in the HSC, the previously used BFE is not suitable anymore. Thus, a synthetic storm developed by FEMA [7] with a return period of 500 years is used; this synthetic storm is slightly more severe than the BFE. The surge behaviour with the MBS was estimated using this storm and an ADCIRC [13] model developed by [17]. Surge levels now vary between 0.1 and 1.8 m in the HSC. As shown in Table 1, this strategy results in the largest reduction of spill risks. Repair and clean-up costs and place vulnerability are also significantly reduced. The AST with the highest vulnerability has a probability of failure of only 0.3 in this case. While the costs associated with this system are considerably higher than the other strategies, the reduction in the repair and clean-up costs justifies 50% of the MBS cost. Moreover, benefits for other infrastructure systems along the HSC are not considered here. The costs of the MBS were obtained from [18].

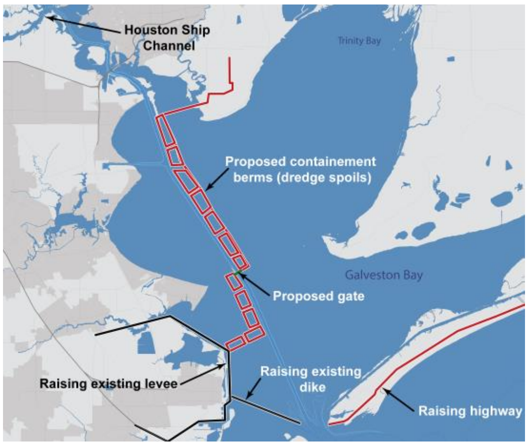

Figure 5: Hazard protection system – Mid Bay Strategy (adapted from [18])

3.4 Comparison of mitigation strategies

The results of the six different mitigation strategies presented above are summarized and compared in Table 1. From this table, structural details alone seem to be the least efficient strategies to reduce the risk of spills and place vulnerability along the HSC. Nonetheless, these strategies significantly reduce expected spill volumes and clean-up costs, greatly reduce the number of highly vulnerable tanks, and are economically advantageous with a cost-benefits ratio of approximately 6. Procedural strategies and hazard protection systems allow for the largest reduction of spill risks, associated economic costs, and place vulnerability. Filling tanks with water before a storm yields the smallest place vulnerability along the HSC and the smallest repair and clean-up cost, while the MBS protection system yields the smallest potential spill volume. However, procedural methods are not always practical and feasible in preparation for a storm, and the MBS requires major investments from different government levels. Structural details may be more dependable than procedural strategies given that they do not require action in the face of an impending storm and do not need massive and complex investments.

Overall, results in Table 1 indicate that no single mitigation strategy is perfect, and that all solutions have practical disadvantages. This leads to the investigation of combinations of procedural strategies and structural details. Such a combination is shown in the last row of Table 1. This combination consists of using anchorage and stiffening rings for all ASTs in the flood zone, and filling with sea water only the tanks subjected to more than 3 m of surge. This leads to a more manageable number of ASTs to fill (less than 200). With this combination, spill volumes and clean-up costs are reduced to low levels, the number of highly vulnerable tanks is reduced to one, and the cost-benefits ratio is nearly 10. However, the effect on place vulnerability is limited. Such results open the path for the use of optimization techniques to determine the best set of strategies for future research.

Table 1: Comparison of the different mitigation strategies at the portfolio level

Mitigation statregy	Spill (10^6 liters)		High vul. ASTs	Cost of mitigation ($Million)		Repair and cleaning cost ($Million)		Cost-benefit ratio		PV index
	Mean	SD		Mean	SD	Mean	SD	Mean	SD	
Baseline	323.9	25.8	109	-	-	4013.9	313.9	-	-	73
Liquid - 6ft	221.5	24.0	38	N/A	N/A	2680.6	289.7	-	-	58
Liquid - Full	52.0	9.2	20	N/A	N/A	631.9	111.3	-	-	31
Water - Full	14.5	0.6	6	N/A	N/A	1.1	0.1	-	-	18
Anchors	148.4	12.7	7	375.3	45.2	1841.4	154.7	5.8	1.0	59
Stiffening rings	115.7	11.3	4	393.6	47.4	1436.6	138.2	6.5	1.1	57
Mid Bay Strat.	1.5	0.5	0	7550.0	433.0	19.9	6.8	0.5	0.0	26
Combination	23.6	5.2	1	393.6	47.4	654.6	75.8	9.5	1.4	40

Finally, with respect to place vulnerability, additional analyses were performed to determine if any strategies were more beneficial to the census tracts with the highest social vulnerability level. Results indicate that none of the mitigation strategies meaningfully reduces spill potentials in these more vulnerable neighbourhoods. This finding is perhaps unsurprising, given that none of the strategies deliberately takes social vulnerability in account. But, it does highlight the need for future research to investigate where and which mitigation strategies should be prioritized to optimally reduce place vulnerability and risks along the HSC.

4 Policy-oriented solutions

4.1 Industry-related policies

Currently, most of the previously discussed mitigation strategies are recommendations or good design practices; no regulations or codes enforce them. AST design codes [1, 2] provide no mandatory provisions to address surge or flood events, and leave the implementation of any protective measures to the owners' discretion. Moreover, many state regulations fail to impose requirements to protect ASTs during surge events. Design codes and regulations should be modified to include provisions for such events and require AST owners or designers to consider and declare methods to prevent flotation or surge buckling. Another industry-related policy concerns the siting of ASTs. Figure 6 shows the evolution of expected spill volume in the HSC for different scenarios from 1999 to 2014. This figure was obtained from the historical AST database developed in [4]. The first scenario shows the actual evolution of spill risks in the HSC, while the second scenario shows the evolution of spill risks if no ASTs were built in the 500-year flood zone between 1999 and 2014. This figure clearly shows that spill risks have increased considerably due to the construction of ASTs in the flood zone. If no tanks were built in the flood zone, risks would have taken a completely different path and decreased. This reduction is attributed to the removal of ASTs from the flood zone by some industries, which highlights the importance of restricting the construction of ASTs in surge-prone areas and encouraging owners to remove their tanks from flood zones. When it is not possible to remove ASTs or build them outside flood zones due to land constraints, ASTs should be designed with adequate protection measures.

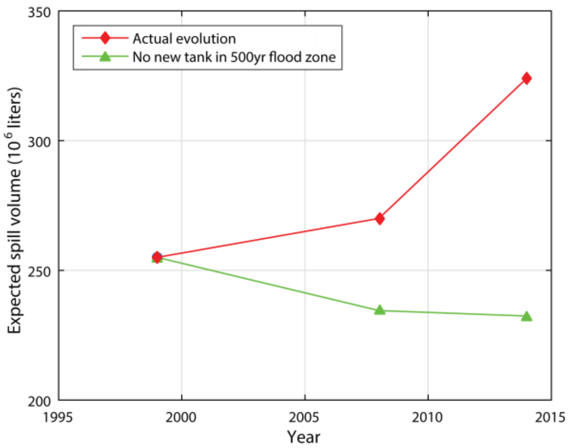

Figure 6: Evolution of spill risks in the HSC between 1999 and 2014

4.2 Community-related policies

Previously investigated strategies and policies mainly focus on reducing the risk of spills along the HSC. Additional policy solutions should be explored to reduce social vulnerability and improve community resilience. One policy could be to implement community resilience planning now being advocated by the National Institute of Standards and Technology [20]; another policy could be to better integrate socially vulnerable communities into port governance and expansion discussions and activities. A fund could even be considered, perhaps, that includes prospective taxes per barrel of stored chemicals, which could be used to educate vulnerable communities about the risks posed by spills events, provide resources to local officials to develop efficient emergency preparation measures, and facilitate the recovery of communities in case of a major spill. Another policy could be to consider the spatial overlap of hazard and social vulnerability (as in Figure (3)) when allocating resources for evacuation. Resources are currently allocated on an equal assistance approach, where all communities subjected to surge are treated equally. However, the most socially vulnerable communities will generally need more resources to evacuate, and an equitable assistance approach may be more appropriate [5]. The integrated model and application to evaluate alternative mitigation strategies in the context of hazard exposure and social vulnerability provides a basis for future policy explorations.

5 Conclusions

This paper proposed a methodology to determine the viability and effectiveness of mitigation strategies to reduce storm surge impacts associated with oil infrastructures. The methodology relies on a model integrating surge hazard exposure, structural vulnerability and fragility modeling of ASTs, and social vulnerability modeling. This model enables the quantification of spill risks, associated economic costs, and place vulnerability during storm surge events, allowing an efficient comparison of different mitigation strategies and providing a useful tool for policymakers and industry managers to make risk-informed decisions. As a proof of concept, the method was applied to the HSC to investigate three main types of mitigation strategies: procedural strategies, structural details, and a hazard protection system. Overall results indicate that no single method is optimal, and that combinations of structural details, procedural methods, and hazard protection systems are more efficient and adequate to reduce the risk of potential storm-induced spills and overall place vulnerability along the HSC. In addition, restricting the construction of ASTs in flood zones is shown to be highly beneficial in changing the temporal evolution of risks. Finally, implementing explicit resilience planning and possibly setting up a resilience fund and developing better evacuation plans for communities along the HSC to increase the capacity of these community to prepare for, respond to, and recover from major spill or storm events were explored. These conclusions provide important insights for understanding and mitigating the risks in coastal areas where people reside alongside oil infrastructures. This methodology can be easily adapted to improve storm surge resiliency in other hurricane prone areas located in the United States or elsewhere in the world. Future work will focus on developing more detailed, policy-oriented solutions and determining more precisely their impacts on industries and surrounding communities. Also, the use of optimization techniques will be investigated to determine the best combinations of mitigation strategies and in which areas of the HSC they should be implemented to minimize risks and improve resilience.

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