Submitted version. Final version here: https://doi.org/10.1016/B978-0-323-85251-7.00012-3
Padgett, J. E., Panakkal, P., & González-Dueñas, C. (2022). Infrastructure impacts and vulnerability to coastal flood events. In Coastal Flood Risk Reduction (pp. 151-165). Elsevier.

Chapter 14. Infrastructure impacts and vulnerability to coastal flood events

Jamie E. Padgett, Pranavesh Panakkal, Catalina Gonzalez-Duenas

Abstract

This chapter provides an overview of the impacts of coastal flood events, namely tropical storms and hurricanes, on coastal infrastructure, leveraging examples from industrial and transportation infrastructure. We emphasize the multi-hazard nature of coastal storm events, producing wind, storm surge, waves, and rainfall, and their impacts on the built environment. Such multi-hazard events can impair the functionality of infrastructure in the short term due to inundation, as well as over longer periods due to damage requiring repair or replacement. Furthermore, these events can have cascading consequences, such as debris generation or spill of hazardous materials which affect health and safety of the public and environment. To illuminate these considerations, case study examples of infrastructure vulnerability and risk analyses are presented from Houston, Texas, USA as well as Rotterdam, Netherlands. These examples highlight the flood risks to above ground storage tanks common in port and industrial facilities as well as the risks to transportation infrastructure affecting mobility around the regions. Future opportunities for philosophical shifts in our approach to design and manage infrastructure in flood prone regions are suggested, emphasizing possibilities for enabling "smart resilience" and for advancing performance-based coastal engineering in temporally evolving coastal settings.

1. Introduction

Coastal infrastructure systems are a vital part of urban and rural development, coastal socio-demographic dynamics, and the global economy. For instance, ports and industrial facilities act as a link in marine and land transportation of goods acting as a major source of employment and an economic catalyst [1]. However, their strategic geographical location also makes them vulnerable to both chronic and punctuated flood related hazards such as sea-level rise or hurricanes events that threaten infrastructure performance now and into the future. Moreover, while flood inundation alone carries significant implications for damage or loss of functionality of various infrastructure (e.g. housing, power systems, transportation, among others), the multi-hazard and compound nature of severe storms along the coast further hampers infrastructure performance. For example, multi-hazards from hurricanes or tropical cyclones, including wind, rain, storm surge and waves, produce complex loading conditions that induce significant damage to structures and infrastructure systems with loss of functionality and other cascading consequences. Flood related damages to coastal infrastructure can result in threats to public safety and quality of life, particularly given risks to housing and transportation systems used in emergency response [2,3]; health and environmental impacts, given potential coastal industrial failures leading to spills of hazardous materials like oil [4,5]; and far-reaching economic implications due to disruption to business operations or infrastructure services, such as intermodal transport of goods [6,7].

Given the importance and potential vulnerability of structures and infrastructure systems to coastal flood events, coastal risk and resilience assessment frameworks have received growing attention in the literature [8,9]. These frameworks often rely on inventory models for the built environment along with understanding of exposure to scenario-based or probabilistic hazards.

The effects of these hazards on infrastructure performance are often assessed through fragility, or vulnerability, models that may vary in fidelity with respect to uncertainty treatment, performance metric of interest, consideration of single- or multi-hazard loads, or incorporation of cascading effects like debris, to name a few. Depending on the aim of the analysis, risk models may moving beyond infrastructure damage or functionality quantification to include such consequences as economic losses or environmental impacts [4,10]. Resilience frameworks increasingly emphasize the value of assessing not only immediate post-event infrastructure performance (vital to emergency response or inspection deployment) but also the long-term functionality and recovery over time (with implications for planning and resilience enhancement interventions) [11]. Furthermore, the role of infrastructure systems in supporting broader community resilience [8,12] and coupled modeling of natural-built-human systems along the coast has received heightened attention in recent years [13,14].

In the next section of this chapter, international case studies of coastal flood impacts on infrastructure are posed to highlight key considerations in risk assessment, leverage potential comparative analyses, and showcase the results from a series of PIRE place-based research studies. The Port of Rotterdam and the Houston-Ship Channel—two of the most important petrochemical complexes and port regions in the world—are adopted as case studies to analyze the effects of coastal hazards on infrastructure systems. Given the vital role of industrial and transportation infrastructure in supporting broader community resilience in such regions, along with the significant consequences of damage or functionality loss, select industrial and transportation infrastructures are considered for the case studies. Furthermore, this chapter will subsequently highlight future opportunities for philosophical shifts in infrastructure design and management in flood prone regions. In particular, concepts “smart resilience” and performance-based coastal engineering are explored as promising paradigms.

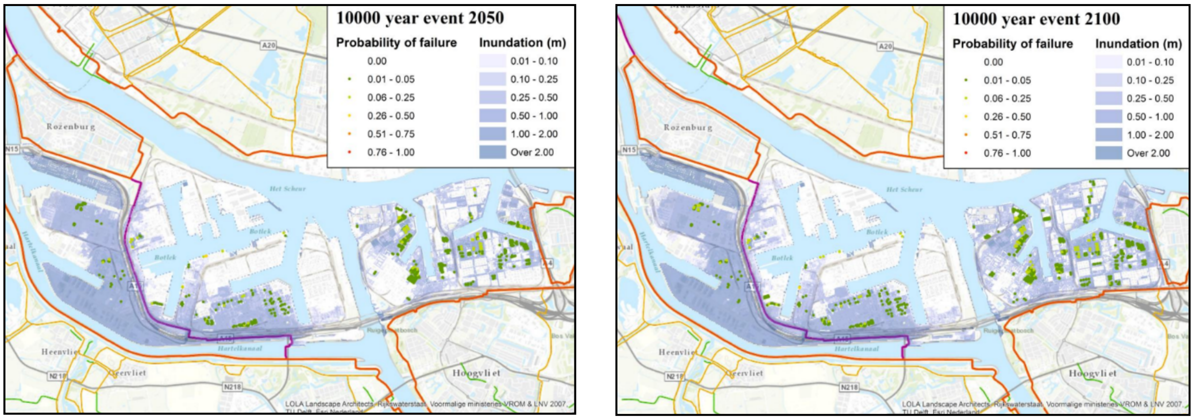
2. International Case Studies of Coastal Flood Impacts on Infrastructure

2.1 Storage Tanks in Coastal Port and Industrial Complexes: The Netherlands and The Gulf Coast

Above Storage Tanks (ASTs) are prevalent in port and industrial complexes, often used to store bulk chemicals such as oil and gas, and are among the most vulnerable components responsible for spillage of hazardous materials during coastal flood events. As the largest port in Europe with 127 square kilometers of port area [15], the Port of Rotterdam has over 3,000 ASTs located in the port regions of Maasvlakte, Europort, and Botlek. Bernier [16] explored the influence of multi-hazard conditions on the AST infrastructure performance, considering the vulnerability of ASTs to flood (as detailed in Chapter 5.3) as well as the potential for debris impact. The Botlek region is located inside the area protected by the Maeslant barrier and dikes and includes ASTs with elevations raging between 0.9 m to 4m above the mean sea level. This relatively low elevation makes the ASTs vulnerable to flood and debris when considering the event of failure of the barrier or overtopping of the dike system [16]. Bernier [16] leveraged the 10,000-year probabilistic flood maps developed by Deltares [17] for the years 2050, and 2100 considering sea-level rise to evaluate the vulnerability of the ASTs to debris impact and flotation failure from flooding. Under these conditions, flood levels and velocities between 0.5 m-2.0 m and 0.5 m/s-2.0 m/s, respectively, are expected for the area. Figure 1 depicts the probability of failure of ASTs (using the parameterized fragility models proposed by Kameshwar and Padgett [18]) for the years 2050 and 2100, under the

10,000-year design event. Results show that the probability of failure does not surpass 30% due to the relatively low flood-elevations levels (i.e. no more than 2.0 m).

Using aerial imagery for the Port of Rotterdam, Bernier [16] identified cars and shipping containers as the principal sources of debris, and verified its flotation potential [19], to evaluate the debris impact risk for the ASTs in the Botlek area. However, preliminary analyses suggested that cars did not inflect significant damage to the ASTs and were neglected in the subsequent assessments. Finite-element models considering imperfection in the tank shell, variation in material properties, internal liquid and external surge loads, as well as hydrodynamic effects were then used to develop an Artificial Neural Network (ANN) regression model covering different types of geometries and debris properties. The ANN model developed by Bernier [16,20] shows a 94% accuracy and was implemented to evaluate the conditional probability of damage of ASTs under shipping container impact. Results show that 146 ASTs and 434 ASTs for the years 2050 and 2100, respectively, are vulnerable to debris impact damage (probability of failure over 50%) in the area. The results of the case study in the Port of Rotterdam underscore the significant impact of cascading failures on infrastructure performance in coastal regions as well as influence of changing climate (e.g. flood estimates future time horizons) on infrastructure risks.



a) b)

Figure 1. Probability of failure of Above Storage Tanks (ASTs) in the Port of Rotterdam for the years a) 2050 and b) 2100 under the 10,000-year design event [21].

By way of comparison, the Houston-Ship Channel (HSC) is the United States Gulf Coast's largest container port [22] and the second largest petrochemical complex in the world [23]. More than 4,500 ASTs located in this region, as opposed to Rotterdam, are susceptible to additional multi-hazard loads due to the occurrence of seasonal hurricane events. Therefore, the vulnerability analyses of ASTs must consider the effects of concurrent wave, surge, and wind loads, as well as the potential of cascading effects such as debris impact, to accurately estimate its risk. Bernier and Padgett [10] developed parameterized buckling and dislocation (for both anchored and unanchored ASTs) fragility models for ASTs under multi-hazard storm conditions. Buckling of ASTs is of particular importance when high wind or water pressures are expected to occur, while dislocation from the ground is usually driven by storm surge effects and can occur under uplift, sliding, or overturning mechanisms [10]. Both failure modes can lead to spill of the ASTs content, the former by the breakage of the tank shell caused by large deformations and the latter by the rupture of connecting pipes. As an illustration, Figure 2 [10] presents the probabilities of failure for a 500-year return period storm (FEMA036 [24]) in the HSC considering the unanchored dislocation parameterized fragility models. The ranges of storm parameters (i.e. surge and wave height, wave period, current and wind velocities) can be found in [10]. The study revealed that while inundation from coastal surge was the primary driver of AST damage, neglecting multi-hazard loading conditions, particularly associated with hydrodynamic forces and wave load effects during storms, could significantly underestimate the damage and spill risks. Furthermore, it is evident that the failure probability of ASTs is significantly higher for the Houston Ship Channel case study than that for the ASTs in the Rotterdam Port, even when considering a much lower return period event (e.g. 500 yr vs 10,000 yr). This can be attributed primarily to the hazard characteristics of the regions and nature of flood events considered, but also in part to the siting and relative elevations of vulnerable infrastructure.

To explore the effects of waterborne debris impacts on ASTs, Bernier and Padgett [25] proposed a probabilistic framework to evaluate the vulnerability of ASTs under the impact of shipping containers. Finite-element models were used to develop parameterized fragility models using logistic regression considering damage to the AST shell and sliding. These fragility models were then used to assess the risk of impact of a case study storage terminal in the HSC. Results showed that disregarding the effect of debris impact significantly underestimates the probability of damage. Moreover, recent work highlights the increased vulnerability of petrochemical infrastructure to a changing climate by analyzing the effects of sea-level rise and shifts in hurricane forward velocity in the expected economic losses in the HSC [23]. Given the expected changes in climate in the coming years, risk and resilience assessments of ASTs in such regions as the HSC should consider both present and future climate conditions in port and industrial complexes, alongside multi-hazard loading effects.

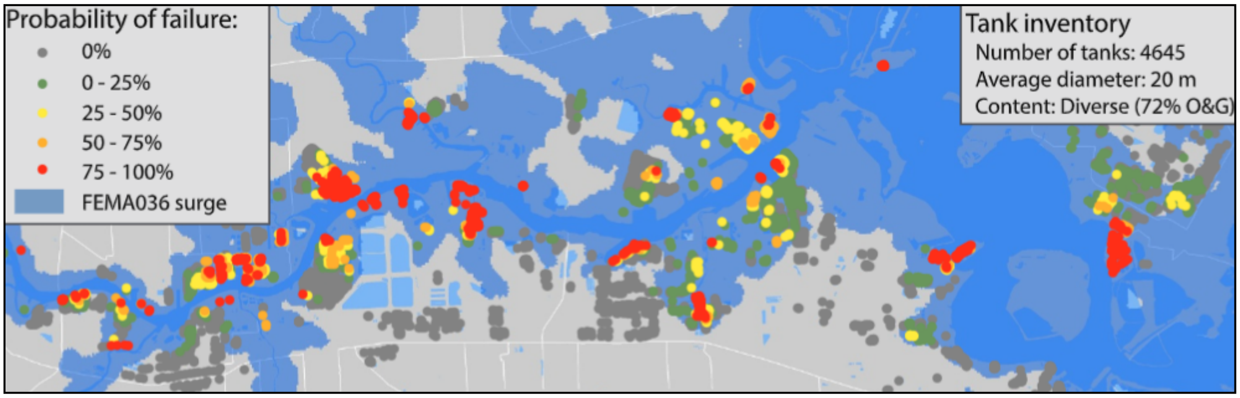


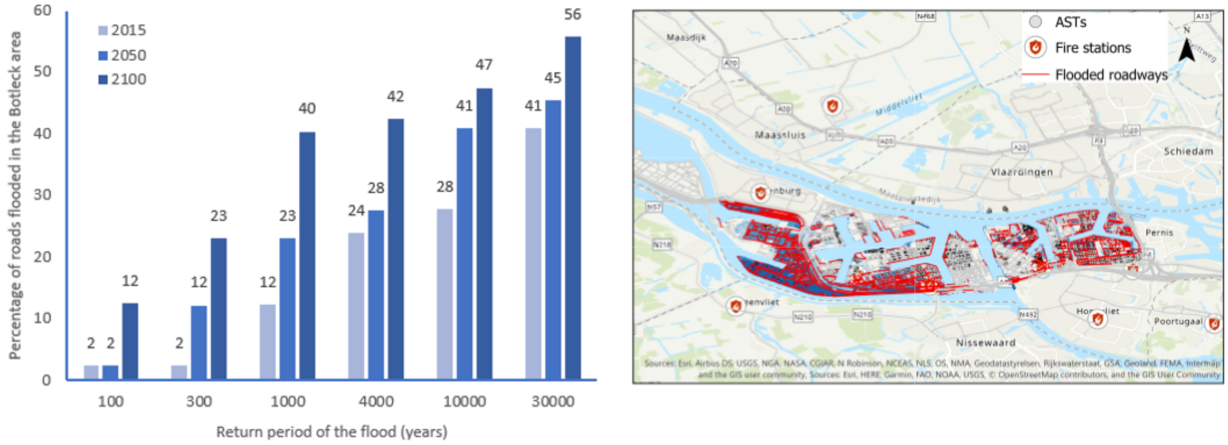
Figure 2. Probability of failure in the HSC under storm FEMA036 (500-year return period storm) considering multi-hazard effects on dislocation of unanchored ASTs [26].

2.2. Transportation Infrastructure: The Netherlands and The Gulf Coast

Flood impact on transportation infrastructure can be either short term or long term. In the short-term, inundated roadways and overtopped bridges could cripple emergency response and isolate several regions from access to critical facilities such as fire stations. These isolated areas are at an elevated risk of potential cascading consequences. For example, flood or storm surge damage to industrial facilities could result in fire or release of hazardous materials, such as the AST spill risk concerns from Section 2.1. If timely access to the failure location is not available for supported repair, containment, or cleanup efforts, the ensuing cascading consequences could include severe environmental and economic losses. This section presents select case studies on the impact of coastal flooding on transportation infrastructure performance, again leveraging the Port of Rotterdam and Gulf Coast regions.

Panakkal [27] investigated the flood impact on road transportation accessibility to at risk industrial facilities, in particular the ASTs located in the Botlek region. This study coupled probabilistic flood maps from Deltares [17] with road network models to identify flooded road and connectivity between fire stations and ASTs. The probabilistic flood hazard maps from Deltares considered potential climate change, sea-level rise, and reliability of flood protection systems for return periods ranging from 100 to 30,000 years for base years 2015, 2050, 2100. Results from Panakkal [27] (Figure 3) show a significant increase in the percentage of flooded roads (in terms of road length) due to potential sea-level rise and climate change. For example, for a 10,000-years return period flood event, while only 12% of roads are flooded in 2015, about 40% of roads will be flooded in 2100 due to potential climate change and sea-level rise. The failure of 40% of roads would significantly limit emergency response access to the vulnerable ASTs in the Botlek area identified by Kameshwar [21] and Bernier [16]. Especially, adjacent residential communities in Rozenburg could be at risk of potential cascading impacts. In addition, considering a possible future increase in flood risk, even a 100-year return period event could cause a failure of 12% of roads in 2100. This study highlights the importance of considering factors such as climate change, sea-level rise, and land-use patterns while estimating flood risk and flood impact on transportation.

In addition to short-term impacts, flood and storm surge could also result in long-term consequences due to structural failure of critical infrastructure components such as roads and bridges. A majority of bridge failures in the United States are due to hydraulic actions [28]. Several studies have also highlighted the vulnerability of bridges to coastal hazards including surge and wave during hurricanes [3,29]. Balomenos [11] proposed a framework to examine the impact of coastal flood events on residents' ability to access health services considering both long-term and short-term impacts. In this study, storm surge models were used to estimate surge conditions at bridges and road links. Bridge fragility functions from Ataei and Padgett [30] were then used to identify bridge damage in addition to temporary road closures due to the overtopping of bridges and roads. While inundation could result in short-term transportation impact, a bridge failure could significantly impact connectivity for a longer period. Finally, network analyses can estimate both short-term and long-term impact of flood hazard on residents' access to health care facilities. Balomenos [11] presented a case study application of this framework for Harris County region, Houston, Texas, using two synthetic storm scenarios. They discovered that infrastructure vulnerability could significantly impact network performance and spatial accessibility. Further, by coupling spatial accessibility with sociodemographic indicators, Balomenos [11] noted that vulnerable populations, such as low-income groups or people over the age of 65, are more likely to have limited access to healthcare facilities even after a low-level storm.



a) b)

Figure 3. a) Percentage of roads flooded in the Botlek area, the Port of Rotterdam, for different return period scenarios and points in time; b) Location of inundated roadways for 10,000-year return period scenario in 2100 [27].

Similarly, Bernier [31] presented a scenario-based framework to access the accessibility of petrochemical facilities by emergency responders and workers during or after a storm surge event. The framework coupled surge models with fragility models of ASTs to identify impacted locations and the likely time-period of potential failures. Storm surge models are then used with bridge fragilities and road network models to determine the short-term and long-term impacts of storm surges. Finally, probabilistic network analysis can estimate the accessibility of impacted facilities by workers or emergency responders. Case study results from Bernier [31] corroborate Balomenos [11] findings and highlight the importance of considering the structural vulnerability of critical transportation infrastructure during flooding or storm surge events. Considering only the short-term impact of storm surges could underestimate the extent and duration of network disruptions. Further, [31] highlight the need to consider and propagate uncertainties associated with network analysis and infrastructure models to facilitate risk-informed decision-making; performing only deterministic network analysis could result in overly conservative accessibility results or bias decision-making.

3. Envisioning the Future of Coastal Infrastructure Design and Management

3.1 Advancing Performance-Based Coastal Engineering

As highlighted in the above-mentioned case studies, coastal settings are susceptible to concurrent and individual hazards that pose major challenges to the design and planning of infrastructure systems. These challenges are expected to grow when considering the changes in climate, land-use, property value, and demographic shifts. Therefore, strategies to cope with the complexity of coastal settings while reducing the risk associated with existing and future infrastructure exposure to coastal flooding are needed to create truly resilient coastal cities.

Since first proposed, performance-based engineering frameworks have establish a comprehensive methodology to evaluate the performance of structures during their service life and provided means to estimate the consequences (usually measured in incurred losses yet not limited to them) of particular designs or retrofitting strategies under specified hazards. This is done by computing the probability of exceedance of a decision variable *DV* (e.g. economic loss, casualties) using the joint-probability distribution of the random variables of the problem at hand which are defined based on six basic steps: (1) performance objectives, (2) hazard analysis, (3) structural characterization, (4) structural analysis, (5) damage analysis, and (6) loss analysis. However, depending on the specific hazard under consideration, more analysis components can be added to the basic methodology. For coastal regions, the performance-based engineering frameworks for wind [32], hurricane [33], and tsunami hazards [34,35] posed key advancements in coastal infrastructure planning by introducing the consideration of multi-hazard and successive analyses, as well as the interaction between the structure and its proximal environment (e.g. fluid-structure interaction, soil-structure interaction). However, the intrinsic dynamic nature of coastal areas, the upcoming changes in climate, and the interdependencies between systems, necessitates the incorporation of a performance analysis that takes into consideration time-varying factors such as structural degradation over time, shifts in frequency and intensity of hazards, as well as potential cascading effects.

To pave a path for future design or risk management of coastal infrastructure, Gonzalez-Duenas and Padgett [36]recently proposed a Performance-Based Coastal Engineering (PBCE) framework that incorporates both time-varying factors and cascading effects in the performance assessment of individual structures and systems, while still accounting for multi-hazard scenarios and environment interactions. Moreover, the methodology is constructed based on a Bayesian network approach, which allows the incorporation of evidence in the model to update the joint probability distribution of the decision variable *DV*. Such a framework provides flexibility in improving performance and risk estimates as new information becomes available. Furthermore, given that a Bayesian network is a probabilistic graphical model, its construction not only unveils correlations and interdependencies between factors and systems, but also helps to disseminate information to stake-holders and bring together experts from different fields, which is key to tackle modern world problems from an integral point of view. Thus, future work should address the use of the PBCE framework to support resilience assessments of infrastructure systems and coastal communities, its use in adaptation engineering to address future challenges, and the effective use of information to enhance our existing probabilistic risk estimates of coastal systems.

3.2 Smart Resilience

Beyond PBCE frameworks, which are particularly poised for supporting future coastal infrastructure design, upgrade, and adaptation, additional opportunities exist to harness the data revolution for improving coastal infrastructure performance. Many communities are becoming increasingly smart and interconnected. New campaigns and data collection efforts in modern cities are expected to yield an unprecedented amount of information on features ranging from infrastructure condition to urban climate to system demands. This poses both challenges and opportunities for enhancing infrastructure resilience and supporting decision-making by organizations affected by or responsible for managing flood risk. A new paradigm of “smart resilience” can pave a path to design and management of infrastructure in coastal regions in which data from smart systems or technologies is leveraged to enhance the system's ability to adapt, to respond, and to recover from stressors.

Several technologies can be leveraged to enhance the resilience of critical infrastructure systems in the face of flood events. For example, the Internet of Things (IoT) is a collection of interconnected sensors integrating the physical world into the internet [37]. Physical sensors such as cameras [38], water level gauges [39], smart sewage [40], accelerometer [41] could provide real-time information on hazard conditions. Further, structural health monitoring devices [42–44] could provide real-time data on infrastructure state and performance. In addition to IoT platforms, real-time situational awareness models based on physics-based simulations [45–48] (, as well as social-media analysis [49–51]and crowdsourcing data [52–54] could provide crucial and timely information on natural hazard, infrastructure state, as well as the community response to disasters. The plethora of data generated by IoT and other sources could vary in temporal and spatial resolution and reliability. These factors necessitate complex data processing and analysis workflows using big data and data fusion methods such as Kalman filters [55]. Past studies have shown the successful application of big data [56] for assessing and managing flood risk [57], for flood detection [58,59], and for facilitating emergency response [60]. Furthermore, surrogate models including the use of machine learning to model flood hazards and their interaction with built infrastructure are gaining interest (e.g. [61–63] and can afford computational efficiency for practical applications of the smart resilience paradigm. Future studies are required to formalize and validate the smart resilience paradigm in various contexts, including but not limited to, infrastructure performance monitoring and risk management, emergency preparedness, disaster response, and recovery.

4. Conclusions

Coastal infrastructure plays an important role in the safety, economic vitality and resilience of a community, yet repeated events have highlighted the vulnerability of various systems to coastal storms and flood related hazards. Both punctuated (e.g. hurricanes) and chronic stressors (e.g. sea level rise) can hinder short and long term performance of systems, such as transportation infrastructure, given inundation as well as physical damage induced by multi-hazard loading. The case study examples from Houston, Texas USA as well as Rotterdam, Netherlands highlight the flood risks to above ground storage tanks common in port and industrial facilities as well as the risks to transportation infrastructure affecting mobility and access around the regions. The results highlight that concurrent multi-hazard effects, like combined wind, surge, and wave, may be particularly important in some regions, like Houston which has significant tropical cyclone or hurricane hazards contributing to its flood risk. In both regions, cascading hazards, such as debris effects, were shown to influence infrastructure risk estimates. In fact such phenomenon have received relatively little attention in coastal infrastructure risk and resilience studies and should be more rigorously addressed in future studies. These international case studies reveal that the risk to diverse infrastructure in both regions may be significantly exacerbated by projected sea level rises in future climate conditions. Opportunities exist to more broadly consider other temporally evolving parameters associated with climate, infrastructure aging and deterioration, or demand shifts. Practices (e.g. design level events) and policies (e.g. regulations or restrictions on siting of infrastructure in hazard-prone regions) in the two regions differ significantly, with The Netherlands tending toward a practice that places heavy weight on risk mitigation and avoidance, and the US one that balances mitigation with response preparedness. Future paradigms in infrastructure design and management may provide opportunities to build on these philosophies. For example, PBCE frameworks, such as the recent Bayesian network formulation, can enable risk-based design or mitigation where time-varying factors, cascading effects, multi-hazard conditions are considered along with possibilities for incorporating new information or evidence in the model. The smart resilience paradigm can promote infrastructure management and adaptation that leverages data sources emerging from smart systems or technologies, such as sensor data, authoritative sources, camera data, or model output. Moving forward, smart technologies offer significant potential for enhancing situational awareness, reducing uncertainty, and supporting decision-making surrounding resilience of infrastructure exposed to coastal flooding. Simultaneously, they also engender challenges in ensuring privacy [37], securing against malicious attacks [64,65], and handling complexity [66] . Thus with new promising paradigm shifts new challenges will continually emerge.

5. References

[1] Dwarakish GS, Salim AM. Review on the Role of Ports in the Development of a Nation. Aquat Procedia 2015;4:295–301. https://doi.org/10.1016/j.aqpro.2015.02.040.

[2] Testa AC, Furtado MN, Alipour A. Resilience of coastal transportation networks faced with extreme climatic events. Transp Res Rec 2015;2532:29–36.

[3] Stearns M, Padgett JE. Impact of 2008 Hurricane Ike on bridge infrastructure in the Houston/Galveston region. J Perform Constr Facil 2012;26:441–52.

[4] Bernier C, Elliott JR, Padgett JE, Kellerman F, Bedient PB. Evolution of Social Vulnerability and Risks of Chemical Spills during Storm Surge along the Houston Ship Channel. Nat Hazards Rev 2017;18:1–14. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000252.

[5] Cruz AM, 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.

[6] Nair R, Avetisyan H, Miller-Hooks E. Resilience framework for ports and other intermodal components. Transp Res Rec 2010;2166:54–65.

[7] Becker AH, Acciaro M, Asariotis R, Cabrera E, Cretegny L, Crist P, et al. A note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society. Clim Change 2013;120:683–95.

[8] Kameshwar S, Cox DT, Barbosa AR, Farokhnia K, Park H, Alam MS, et al. Probabilistic decision-support framework for community resilience: Incorporating multi-hazards, infrastructure interdependencies, and resilience goals in a Bayesian network. Reliab Eng Syst Saf 2019;191:106568.

[9] Kammouh O, Gardoni P, Cimellaro GP. Probabilistic framework to evaluate the resilience of engineering systems using Bayesian and dynamic Bayesian networks. Reliab Eng Syst Saf 2020;198:106813. https://doi.org/10.1016/j.ress.2020.106813.

[10] Bernier C, Padgett JE. Fragility and risk assessment of aboveground storage tanks subjected to concurrent surge, wave, and wind loads. Reliab Eng Syst Saf 2019;191:106571. https://doi.org/10.1016/j.ress.2019.106571.

[11] Balomenos GP, Hu Y, Padgett JE, Shelton K. Impact of coastal hazards on residents ’ spatial accessibility to health services. J Infrastruct Syst 2019;25:04019028.

https://doi.org/10.1061/(ASCE)IS.1943-555X.0000509.

[12] Koliou M, van de Lindt JW, McAllister TP, Ellingwood BR, Dillard M, Cutler H. State of the research in community resilience: Progress and challenges. Sustain Resilient Infrastruct 2020;5:131–51.

[13] Fereshtehnejad E, Gidaris I, Rosenheim N, Tomiczek T, Padgett JE, Cox DT, et al. Probabilistic risk assessment of coupled natural-physical-social systems: the cascading impact of hurricane-induced damages to civil infrastructure in Galveston, Texas. In Review: 2020.

[14] Ellingwood BR, Cutler H, Gardoni P, Peacock WG, van de Lindt JW, Wang N. The centerville virtual community: A fully integrated decision model of interacting physical and social infrastructure systems. Sustain Resilient Infrastruct 2016;1:95–107.

[15] Port of Rotterdam. The smartest port in the world 2019. https://www.portofrotterdam.com/sites/default/files/the-worlds-smartest-port-port-of-rotterdam-publieksfolder-2019-en.pdf (accessed November 15, 2020).

[16] Bernier C. Impacts of water driven debris impacts on above storage tanks. In: Kothuis BB, Lee Y, Brody S, editors. NSF-PIRE Coast. flood risk Reduct. program. Authentic Learn. Transform. Educ. Vol. I - 2015-2017, 2018, p. 248.

[17] Deltares. Potentiële inundatie Botlek 2015.

[18] Kameshwar S, Padgett JE. Storm surge fragility assessment of above ground storage tanks. Struct Saf 2018;70:48–58.

[19] Korswagen PA. Structural damage to masonry housing due to earthquake-flood multi-hazards. TU Delft, 2016.

[20] Bernier C, Padgett JE. Neural networks for estimating storm surge loads on storage tanks 2019.

[21] Kameshwar S. Understanding vulnerability and acceptable flood risk to storage tanks. In: Kothuis BB, Lee Y, Brody S, editors. NSF-PIRE Coast. flood risk Reduct. program. Authentic Learn. Transform. Educ. Vol. I- 2015-2017, 2018, p. 248.

[22] Port Houston. Statistics 2019. https://porthouston.com/about-us/statistics/ (accessed November 15, 2020).

[23] Ebad Sichani M, Anarde KA, Capshaw KM, Padgett JE, Meidl RA, Hassanzadeh P, et al. Hurricane risk assessment of petroleum infrastructure in a changing climate. Front Built Environ 2020;6:104.

[24] Ebersole BA, Massey TC, Melby JA, Nadal-Caraballo NC, Hendon DL, Richardson TW, et al. Interim report—Ike Dike concept for reducing hurricane storm surge in the Houston-Galveston region. Jackson State Univ, Jackson, MS 2015.

[25] Bernier C, Padgett JE. Probabilistic assessment of storage tanks subjected to waterborne debris impacts during storm events. J Waterw Port, Coastal, Ocean Eng 2020;146:4020003.

[26] Bernier C, Padgett JE. Fragility and risk assessment of aboveground storage tanks subjected to concurrent surge, wave, and wind loads. Reliab Eng Syst Saf 2019;191:106571.

[27] Panakkal P. Flood impacts on emergency response accessibility and mobility in the Port of Rotterdam. PIRE Coastal Flood Risk Reduction Program: 2019.

[28] Cook W, Barr PJ, Halling MW. Bridge failure rate. J Perform Constr Facil 2015;29:4014080.

[29] Padgett J, Desroches R, Nielson B, Yashinsky M, Kwon OS, Burdette N, et al. Bridge damage and repair costs from Hurricane Katrina. J Bridg Eng 2008;13:6–14. https://doi.org/10.1061/(ASCE)1084-0702(2008)13:1(6).

[30] Ataei N, Padgett JE. Probabilistic modeling of bridge deck unseating during hurricane events. J Bridg Eng 2013;18:275–86.

[31] Bernier C, Gidaris I, Balomenos GP, Padgett JE. Assessing the accessibility of petrochemical facilities during storm surge events. Reliab Eng Syst Saf 2019;188:155–67.

[32] Ciampoli M, Petrini F, Augusti G. Performance-Based Wind Engineering: Towards a general procedure. Struct Saf 2011;33:367–78. https://doi.org/10.1016/j.strusafe.2011.07.001.

[33] Barbato M, Petrini F, Unnikrishnan VU, Ciampoli M. Performance-Based Hurricane Engineering (PBHE) framework. Struct Saf 2013;45:24–35. https://doi.org/10.1016/j.strusafe.2013.07.002.

[34] Attary N, Unnikrishnan VU, van de Lindt JW, Cox DT, Barbosa AR. Performance-Based Tsunami Engineering methodology for risk assessment of structures. Eng Struct 2017;141:676–86. https://doi.org/10.1016/j.engstruct.2017.03.071.

[35] Attary N, Van De Lindt JW, Barbosa AR, Cox DT, Unnikrishnan VU. Performance-Based Tsunami Engineering for Risk Assessment of Structures Subjected to Multi-Hazards: Tsunami following Earthquake. J Earthq Eng 2019:1–20. https://doi.org/10.1080/13632469.2019.1616335.

[36] Gonzalez-Duenas C, Padgett JE. A Performance-Based Coastal Engineering Framework. In Preparation: 2020.

[37] Van Ackere S, Verbeurgt J, De Sloover L, Gautama S, De Wulf A, De Maeyer P. A review of the internet of floods: Near real-time detection of a flood event and its impact. Water 2019;11:2275.

[38] Lo S-W, Wu J-H, Lin F-P, Hsu C-H. Visual sensing for urban flood monitoring. Sensors 2015;15:20006–29.

[39] Perumal T, Sulaiman MN, Leong CY. Internet of Things (IoT) enabled water monitoring system. 2015 IEEE 4th Glob. Conf. Consum. Electron., IEEE; 2015, p. 86–7.

[40] Granlund D, Brännström R. Smart city: the smart sewerage. 37th Annu. IEEE Conf. Local Comput. Networks-Workshops, IEEE; 2012, p. 856–9.

[41] Chiang C-T. Design of a CMOS MEMS accelerometer used in IoT devices for seismic detection. IEEE J Emerg Sel Top Circuits Syst 2018;8:566–77.

[42] Mahmud MA, Bates K, Wood T, Abdelgawad A, Yelamarthi K. A complete internet of things (IoT) platform for structural health monitoring (shm). 2018 IEEE 4th World Forum Internet Things, IEEE; 2018, p. 275–9.

[43] Tokognon CA, Gao B, Tian GY, Yan Y. Structural health monitoring framework based on Internet of Things: A survey. IEEE Internet Things J 2017;4:619–35.

[44] Abdelgawad A, Yelamarthi K. Structural health monitoring: Internet of things application. 2016 IEEE 59th Int. Midwest Symp. Circuits Syst., IEEE; 2016, p. 1–4.

[45] Fang Z, Bedient PB, Buzcu-Guven B. Long-term performance of a flood alert system and upgrade to FAS3: A Houston, Texas, case study. J Hydrol Eng 2011;16:818–28.

[46] Panakkal P, Juan A, Garcia M, Padgett JE, Bedient P. Towards Enhanced Response: Integration of a Flood Alert System with Road Infrastructure Performance Models. Struct. Congr. 2019 Build.

Nat. Disasters, American Society of Civil Engineers Reston, VA; 2019, p. 294–305.

[47] University LS. CERA-Coastal Emergency Risk Assessment n.d. https://cera.coastalrisk.live/ (accessed November 15, 2020).

[48] SSPEED Center. FAS5-TMC Rice Flood alert system. Rice Univ 2020. http://fas5.org/home.html (accessed November 15, 2020).

[49] Jongman B, Wagemaker J, Romero BR, De Perez EC. Early flood detection for rapid humanitarian response: harnessing near real-time satellite and Twitter signals. ISPRS Int J Geo-Information 2015;4:2246–66.

[50] de Bruijn JA, de Moel H, Jongman B, Wagemaker J, Aerts JCJH. TAGGS: grouping tweets to improve global geoparsing for disaster response. J Geovisualization Spat Anal 2018;2:2.

[51] De Longueville B, Smith RS, Luraschi G. " OMG, from here, I can see the flames!" a use case of mining location based social networks to acquire spatio-temporal data on forest fires. Proc. 2009 Int. Work. Locat. based Soc. networks, 2009, p. 73–80.

[52] Liu C-C, Shieh M-C, Ke M-S, Wang K-H. Flood prevention and emergency response system powered by google earth engine. Remote Sens 2018;10:1283.

[53] See L. A review of citizen science and crowdsourcing in applications of pluvial flooding. Front Earth Sci 2019;7:44.

[54] Wang R-Q, Mao H, Wang Y, Rae C, Shaw W. Hyper-resolution monitoring of urban flooding with social media and crowdsourcing data. Comput Geosci 2018;111:139–47.

[55] Chen Z. Bayesian filtering: From Kalman filters to particle filters, and beyond. Statistics (Ber) 2003;182:1–69.

[56] Pollard JA, Spencer T, Jude S. Big Data Approaches for coastal flood risk assessment and emergency response. Wiley Interdiscip Rev Clim Chang 2018;9:e543.

[57] Sood SK, Sandhu R, Singla K, Chang V. IoT, big data and HPC based smart flood management framework. Sustain Comput Informatics Syst 2018;20:102–17.

[58] Cian F, Marconcini M, Ceccato P. Normalized Difference Flood Index for rapid flood mapping: Taking advantage of EO big data. Remote Sens Environ 2018;209:712–30.

[59] Anbarasan M, Muthu B, Sivaparthipan CB, Sundarasekar R, Kadry S, Krishnamoorthy S, et al. Detection of flood disaster system based on IoT, big data and convolutional deep neural network. Comput Commun 2020;150:150–7.

[60] Smith L, Liang Q, James P, Lin W. Assessing the utility of social media as a data source for flood risk management using a real-time modelling framework. J Flood Risk Manag 2017;10:370–80.

[61] Mosavi A, Ozturk P, Chau K. Flood prediction using machine learning models: Literature review. Water 2018;10:1536.

[62] Bass B, Bedient P. Surrogate modeling of joint flood risk across coastal watersheds. J Hydrol 2018;558:159–73.

[63] Mobley W, Sebastian A, Blessing R, Highfield WE, Stearns L, Brody SD. Quantification of Continuous Flood Hazard using Random Forrest Classification and Flood Insurance Claims at Large Spatial Scales: A Pilot Study in Southeast Texas. Nat Hazards Earth Syst Sci Discuss 2020:1–22.

[64] Zhu C, Leung VCM, Shu L, Ngai EC-H. Green internet of things for smart world. IEEE Access 2015;3:2151–62.

[65] Alaba FA, Othman M, Hashem IAT, Alotaibi F. Internet of Things security: A survey. J Netw Comput Appl 2017;88:10–28.

[66] Jovanović A, Vollmer M. Do Smart Technologies Improve Resilience Of Critical Infrastructures? Crit Infrastruct Prot Rev 2017:37.