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CHAPTER 19

Flood risk reduction for Galveston Bay: Preliminary design of a coastal barrier system

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Introduction

Many coastal areas around the world are densely populated and at risk from flooding. To address coastal hazards, regions have taken different approaches, ranging from a prevention-based strategy to one that relies largely on the mitigation of impacts. The local choice of strategy is influenced by geographical factors (e.g., nature of the hazard, geography of the region, and density of population and assets) as well as financial and cultural aspects (e.g., costs and benefits of measures and role of government) and preference for collective vs individual arrangements.

The flood risk management strategy in the Netherlands is a key example of the first strategy, i.e., prevention through collective arrangements. In the 20th century, the Dutch implemented a coastal protection system based on the principle of shortening the coastline. After the flood of 1916, a 30-km closure dam (Afsluitdijk) was built to close off a large estuary. The system protects the middle of the country—including the capital of Amsterdam—from storm surge. After the 1953 storm surge disaster—which killed more than 1800 people—a series of dams and storm surge barriers were built in the southwest of the country to shorten the directly exposed coastline by hundreds of kilometers.

Whereas the Dutch approach focuses on prevention, flood management in the United States has traditionally focused on a multilayered approach The latter aims to combine prevention efforts with mitigation. The US flood management in recent decades seems to have become more prevention-based strategy. After hurricane Katrina, a large-scale flood protection system was built around New Orleans, and studies on barrier schemes are ongoing in several parts of the United States, for example, in the New York/New Jersey region (USACE, 2019).

The Galveston Bay area is also at significant risk of flooding and large-scale protection plans are being considered. Since 2012, Dutch researchers and students have participated

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in the exploration of a possible implementation of Dutch flood risk management concepts for this region. This effort involved over 50 scientists and students from multiple disciplines (mainly civil engineering, architecture, policy, and management) and results are summarized by Kothuis, Brand, Sebastian, Nillesen, and Jonkman (2015).

This chapter provides an overview of some of these efforts in two key areas: risk-based evaluation of strategies for the region ("Setting the scene: Risk-based evaluation of strategies" section) and a "Preliminary design of a coastal spine system" section. The chapter concludes with a "Closing discussion" section. The focus of this chapter is on coastal flooding and storm surge. Rain-induced floods are not directly considered here.

The relevance of this chapter extends beyond the study area. It addresses the challenges associated with finding an appropriate risk-reduction strategy in situations where many combinations of (interdependent) measures are possible. In addition, it highlights how a multidisciplinary "Research by Design" approach can be adopted to find a coastal strategy that matches the local situation and objectives.

Setting the scene: Risk-based evaluation of strategies

Large, complex coastal regions—such as the Galveston Bay region and the Dutch delta—often require a combination of interventions to reduce flood risk to acceptable levels. To inform planning and decision-making, multiple alternative strategies can be analyzed and evaluated based on metrics such as costs, risk reduction, and societal and environmental impacts. As part of previous work, a risk-based modeling framework for such evaluations was developed and applied to Galveston Bay area (Van Berchum et al., 2018). This rapid probabilistic model simulates and evaluates the risk reduction and costs of many flood risk reduction strategies, taking into account interdependencies between measures. The simulation includes hydraulic calculations, damage calculations, and the effects of measures for different return periods.

Many measures and strategies are possible for the Galveston Bay area, ranging from coastal defense to in-bay measures and barriers that specifically protect the Houston area—see Fig. 1 for an overview. A preliminary investigation using the risk-based model compared the coastal spine solution with a mid-bay barrier and no action. This highlighted that the coastal spine would be the most expensive alternative economically, but would provide the greatest risk reduction by maximizing the protected area. It also shortens the coastline, leading to potential cost savings compared to other strategies that would rely on perimeter protection around the bay. Therefore, in the remainder of this chapter design efforts for the coastal spine are reported. It should be noted that in-bay alternatives and features were also elaborated on as part of the collaborative studies, see Kothuis et al. (2015) and the discussion section in this chapter.

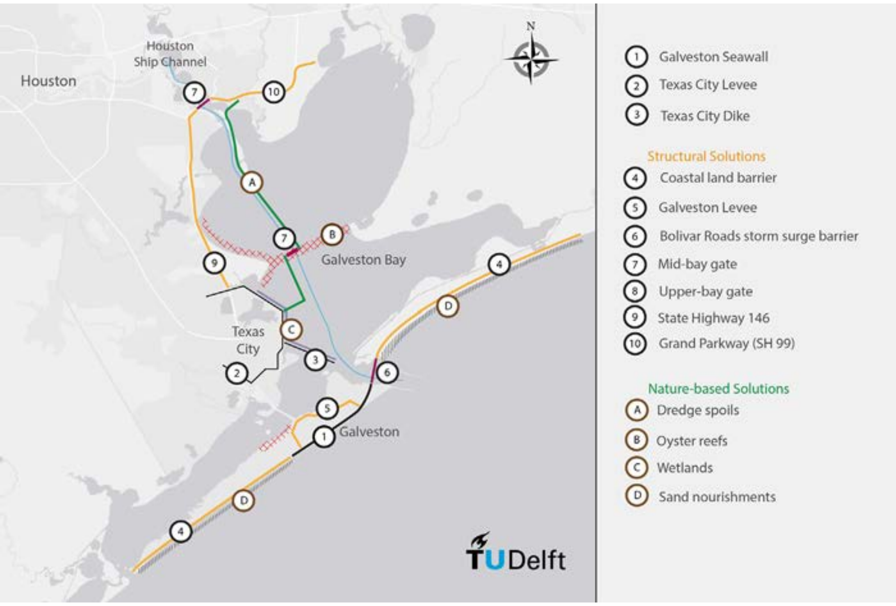

Fig. 1 Overview of potential measures for Galveston Bay (Van Berchum et al., 2018). *(Adapted after a figure developed by the SSPEED Center at Rice University. Included in a chapter by P.B. Bedient on p. 49 of Kothuis, B. L. M, Brand, A. D., Sebastian, A. G., Nillesen, A. L., & Jonkman, S. N. (2015).* Delft delta design: The Houston Galveston Bay region, Texas, USA*).*

Preliminary design of a coastal spine system

Approach and system overview

Following the devastating coastal flooding caused by hurricane Ike in 2008, a coastal spine system was proposed to protect the Galveston Bay area (Merrell, Reynolds, Cardenas, Gunn, & Hufton, 2011). It is also referred to as the Ike Dike. It would provide a barrier against storm surges into the bay and is conceptually similar to barriers built in the Netherlands to shorten the Dutch coastline. This chapter summarizes design work done on the Coastal Spine system by Dutch and American experts between 2012 and 2019. In different design stages (sketch and early conceptual design—referred to here as preliminary design), different barrier concepts were explored based on requirements for functional and engineering performance and landscape integration. The main function of the system is to prevent the inflow of the hurricane surge into the bay and to protect the areas behind it. The designs for the storm surge barriers are based on boundary conditions for navigation and environmental flow to minimize impacts on these functions. In addition, integration of the new features into the landscape and ecosystem were

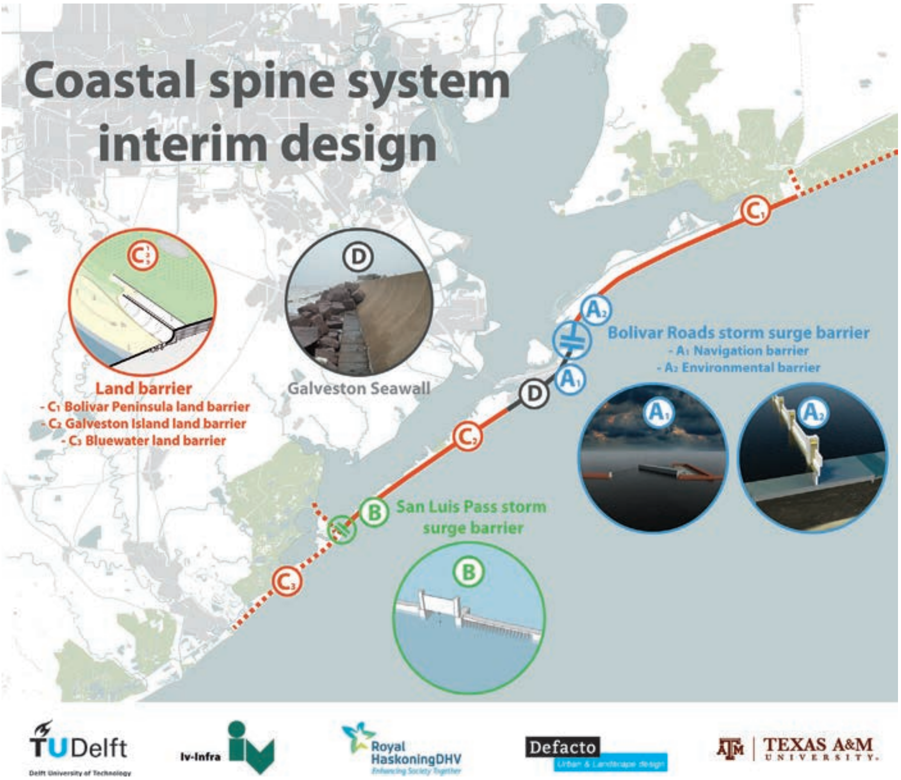

Fig. 2 Visualization of the coastal spine system (Jonkman et al., 2015).

important considerations. Further details for the concepts summarized below can be found in the reports “Coastal spine interim design” (Jonkman et al., 2015) and “Land barrier preliminary design” (Van Berchum, de Vries, & de Kort, 2016) reports.

Fig. 2 provides an overview of the system and its main elements. The barrier system includes storm surge barriers in the Bolivar Roads inlet (A1 and A2) and San Luis Pass (B). The land barriers (C1, C2, C3) are designed to protect Galveston Island and Bolivar Peninsula and stop or limit overland flow into the bay.

The total length of the coastal spine presented in Fig. 2 is 94 km (58.5 miles), consisting of 90 km (56 miles) of land barriers and two storm surge barriers with a length of 4 km (2.5 miles). Some sections of the barrier (indicated as dashed lines) require further investigation. These include the western edge of the land barrier along the Bluewater Highway and the connection of the eastern end of the land barrier near the community of High Island.

Table 1 shows the key hydraulic boundary conditions for the land and storm surge barriers. These are preliminary estimates that should be improved in further studies.

Table 1 Hydraulic boundary conditions for the design.

	Protection level	Life time (years)	Associated maximum water level in the Gulf of Mexico (h)[a] and significant wave height (H_s)
Land barrier	1/100 per year	50–100	$h = 5.7$ m and $H_s = 6.9$ m
Storm surge barriers	1/10,000 per year	100–200	$h = 7$ m and $H_s = 8.0$ s

[a] The estimate includes a somewhat conservative estimate of sea level rise of about 1 m over the 100-year lifetime.

Based on Jonkman, S. N., Lendering, K. T., van Berchum, E. C., Nillesen, A., Mooyaart, L., de Vries, P., et al. (2015). *Coastal spine system—Interim design report* and Van Berchum, E. C., de Vries, P. A. L., & de Kort, R. P. J. (2016). *Galveston Bay area land barrier preliminary design*. TU Delft report.

For the storm surge barrier, a high protection level—similar to the level for Dutch coastal defenses—has been set because it serves to protect the entire metropolitan area around Galveston Bay. A lower level of protection was used for the land barrier because it is more adaptable than the storm surge barrier. Additional resilience requirements can be applied to the land barrier so that it can still limit inflow into Galveston Bay for more extreme events (e.g., 1/1000 per year). For the given 100-year protection level, it is expected that the existing Galveston seawall can still be utilized for protection—albeit with some adaptations.

Bolivar Roads storm surge barrier

The Bolivar Roads barrier consists of two sections: a navigational section with the main requirement of free passage for ships, and an environmental section for water and environmental flows.

Navigational section gates

For the navigational section, initial explorations with barrier experts considered two types of floating gates: floating sector gates (like the Dutch Maeslant barrier near Rotterdam) and a single barge gate. The barge gate was chosen as a preferred concept because a sector gate is less suitable to handle a negative head situation: water levels in Galveston Bay may be higher than those in the Gulf of Mexico due to the potential back surge during a hurricane. In such a situation, sector gates could be "pushed" out of their hinges.

A preliminary estimate of 220 m is used for the width of the navigational section. This would allow for a single, two-way shipping lane, while a Post/New Panamax tanker is assumed as a design vessel. Fig. 3 (left panel) shows the barge gate of the navigation section and the closing procedure. It would normally close during the forerunner surge to limit water levels on Galveston Bay.

The barge gate is designed as a partly floating structure that distributes the loads toward the abutments on both sides. The foundation of these concrete abutments can consist of a deep pile foundation with a mixed group batter piles (tension and pressure)

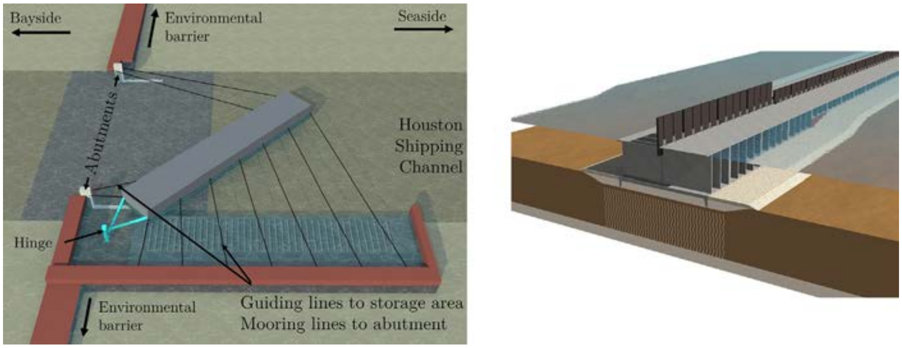

Fig. 3 Bolivar Roads storm surge barrier concepts: left: a barge gate for the navigational section (Smulders, 2014); right: a vertical liftgate for the environmental section (De Vries, 2014).

or a deep foundation of (pneumatic) caissons or (a coupled pair of) cellular cofferdams. The dynamics of the barrier in various phases of operation has been investigated in the thesis of Smulders (2014). This showed that most movements remain within tolerable limits. Critical aspects to be considered further are the landing operation and the load case under a negative head. The horizontal load transfer and dynamics of the barrier can be further optimized by considering the quantity of water allowed within the barge.

The chosen concept of floating barriers is similar to the floating barriers of the Maeslant barrier in the Netherlands in that some over- and underflow are allowed to reduce the amount of material and the cost of the structure. This concept introduces high flow velocities under the barrier gate when it is in the closed position. Under water, heavy scour protection is required to form a stable sill. It should consist of large concrete elements below the total gate width and large rock protection further away from the barrier in the perpendicular direction. During a storm closure, some overtopping of water is allowed as there is a large storage capacity in Galveston Bay. A structural design in steel was made and the gate consists of S355 steel and the weight is approximately 32,000 tons (Jonkman et al., 2015; van der Toorn et al., 2014). An alternative design in concrete was made by Karimi (2014).

Key topics for further exploration include hinges, a suitable foundation concept that is feasible in the local soft soil conditions, exact barrier dimensioning given navigation requirements and operation, and alternative barrier concepts, such as a closed barge gate system, which does not allow underflow and overflow.

Environmental section gates

The main purpose of the environmental section is to allow for tidal exchange in normal conditions and closure during storm conditions. For the environmental section, several concepts were explored at a somewhat less detailed level. These include

- Vertical lifting gates—similar to those used at the Eastern Scheldt barrier in the Netherlands. The gates can be embedded in a caisson placed on the seabed and prepared with vertical underwater drainage, placed on a shallow wide foundation.
- Vertical radial gates on a deep pile foundation.

More innovative gate concepts were also explored, such as

- A rotating gate, with a plate that is in a horizontal position in normal conditions, but rotates to a vertical position during the closure;
- Inflatable gates using rubber sheets. During closing, the sheets are filled with water and air. This concept has been applied at the Ramspol barrier in the Netherlands and has been further elaborated for Bolivar Roads by Van Breukelen (2013).

A promising concept with regard to operation, maintenance, reliability, and cost seems to be a system with vertical lift gates Fig. 3 (right). The local soil conditions are critical in further developing this solution.

In order to minimize the impacts on tidal flows, in-bay tide levels, and ecosystems, it is important that the storm surge barrier is as "open" as possible in normal conditions, i.e., the tidal flow passing through as naturally as possible. In the preliminary designs presented, the opening of the cross section at Bolivar Roads would be 70%–80% of the original cross section, leading to a limited reduction (~5%) of the tidal range (Ruijs, 2011). Further optimization of barrier design and investigation of barrier effects on tidal flows, morphology and ecology are important topics for further studies.

A barrier solution should also be considered for the San Luis Pass. The width of this opening is about 1000 m. Without a barrier, a hurricane-induced surge will result in significant inflows into Galveston Bay and scour. A navigational gate (such as a liftgate) for smaller ships combined with a number of environmental gates could be considered as barrier solutions.

Land barrier

The land barrier plays a crucial role in protecting the Galveston Bay metropolitan area. Concepts for the land barrier have been explored based on a spatial analysis of the landscape by architects (Van Berchum et al., 2016). Fig. 4 (top panel) shows the results of this analysis. A distinction is made between (a) open landscape sections; (b) the Galveston seawall; (c) residential sections where the main island road is relatively close to the shoreline (100–150 m); and (d) residential sections where the road is further from the shoreline. Based on the landscape and available space, optimal integration of barrier solutions can be explored. Differentiation of barrier solutions and placement between locations may also be considered to allow optimal integration and alignment with the preferences of local stakeholders.

Several land barrier solutions have been developed. One option concerns a coastal dike. A preliminary design has been made assuming the hydraulic boundary conditions

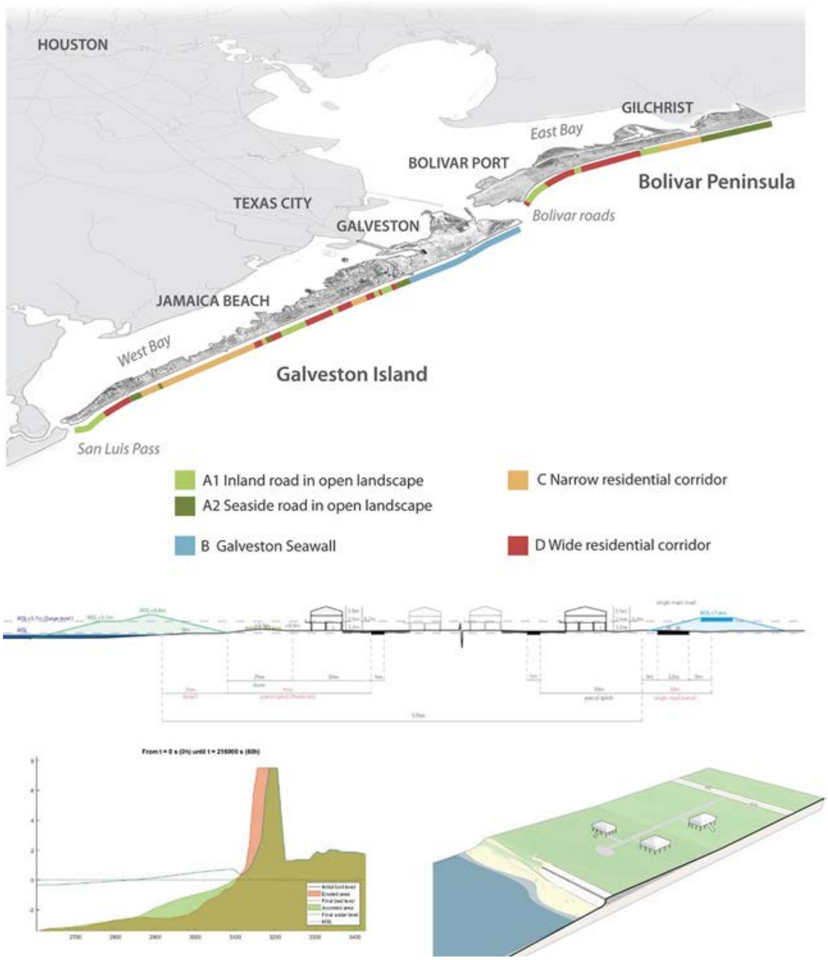

Fig. 4 Land barrier preliminary design: top: landscape analysis (Van Berchum et al., 2016); middle: cross section of the coastal dike design for the wide residential section (Van Berchum et al., 2016); bottom: alternative coastal protection concepts: dune (Rodriguez Galvez, 2019) and fortified dune (Jonkman et al., 2015).

with a return period of 100 years (Table 1). An overtopping limit of 50 L/s/m has been assumed, which in extreme cases allows for some erosion of embankments. There are two main choices for the positioning of the coastal dike, directly on the shoreline or at the location of the main road on the island (Fig. 4 middle panel). A shoreline positioning would result in a larger dike with a berm and an estimated elevation of MSL +8.8 m. It would protect all houses on the island. The dike would consist of a clay core and a hard revetment on the coastal side to withstand wave impacts. A drawback of the shoreline alternative is that it would affect the existing beach and could exacerbate erosion.

The inland option would allow for a somewhat lower elevation of the land barrier (MSL +7.5 m), but leaves houses on the southern side of the road exposed. In further exploration of land barrier alternatives, it is highly relevant to consider designing for further overtopping resilience for higher overtopping rates (>500 l/s/m), which would require armoring of the inner slope, for example, with asphalt or aggregate (e.g., Elastocoast) revetments (Van der Sar, 2016).

Alternative concepts have also been explored. In the MSc thesis of Rodriguez Galvez (2019), a **dune design** was made. During (design) storm conditions, a dune will be heavily eroded. The dune is designed so that wave overtopping is limited and the remaining profile would still be sufficient to avoid breaching and protect the area behind the dune. The numerical XBeach model was used to verify the performance of the dune in design conditions (see Fig. 4, lower left panel). This resulted in a dune profile with a crest elevation of MSL +7.5 m, width at MSL of 100 m, slopes of 1:3, and a dune crest width of 55 m. Aspects of the dune solution that require further investigation include morphological effects and long-term erosion, and associated management and maintenance practices. The availability (and costs) of large volumes of sand and the environmental impacts of sand mining and construction also requires further attention.

A very interesting land barrier solution to explore further is the **fortified dune** (or dike in dune). Such a hybrid defense would combine a structural defense with sand cover (Almarshed, Figlus, Miller, & Verhagen, 2019). This type of solution has been implemented in the Dutch coastal town of Noordwijk. It fits well into the natural coastal landscape, the footprint is smaller than for dunes, and the hard core would allow resilience to events that overtop or overflow the defense. It is recommended that the performance of fortified dune solution under storm conditions be further investigated, including potential synergies between dune erosion (leading to wave breaking) and load reduction on the hard structure. Further development of design practices and guidelines is also required to enable implementation.

Cost estimation

Due to the preliminary stage of design and a large number of factors still unknown, it is a challenge to produce a reliable and robust cost estimate. However, using assumptions and knowledge from previous projects, it is possible to provide a preliminary and indicative (but "rough") cost estimate.

Unit costs for storm surge barriers are reported in review studies for barriers around the world by Mooyaart and Jonkman (2017) and later updated in Kluijver, Dols, Jonkman, and Mooyaart (2019). Due to the complexity of the barriers, the costs are high: ranging from 1 to 4 million US$ per meter of span, with an average of 3 Million US$/m (2.5 MEuro) per meter span. This unit cost was adopted for an initial estimate of the navigational section. The environmental section is envisioned in a shallower area and allows for more repetition of elements and construction. Here a unit cost of 2 MUS$/m is

Table 2 Preliminary cost estimate for the coastal spine system features.

Element class	Location	Length (m)	Unit costs (M$/m)	Element costs (M$)	Bandwidth (%)
Storm surge barrier	Bolivar Roads (Navigational)	200	3	600	50
	Bolivar Roads (Environmental)	2800	2	5600	50
	San Luis Pass	1000	–	330	50
Land barrier	Bolivar Peninsula	40,000 (25 mile)	0.045	1800	30
	Galveston Island	30,000 (18.6 mile)	0.045	1350	30
	Bluewater Highway	20,000 (12.5 mile)	0.045	900	30
Total				**10,580**	**40**

Based on Jonkman, S. N., Lendering, K. T., van Berchum, E. C., Nillesen, A., Mooyaart, L., de Vries, P., et al. (2015). *Coastal spine system—Interim design report.*

adopted, similar to the Eastern Scheldt barrier and an additional estimate of 330 MUS$ for the San Luis Pass is included. For the land barrier, the dike alternative was considered. Unit costs from previous projects (Jonkman, Hillen, Nicholls, Kanning, & van Ledden, 2013) and a more material volume-based approach were considered. Both resulted in a cost estimate of the construction of a coastal dike of about 45 M$ per kilometer.

Table 2 presents the preliminary cost estimate for the current system at 10.6 B$ with a bandwidth between 6.3 and 14.8 B$. Again, the cost estimate will depend heavily on the designs and choices for the various system features.

The cost estimate does not yet include other potential system features, such as additional flood risk reduction measures in Galveston Bay and the Galveston ring levee. Also, many measures such as environmental restoration and mitigation and land acquisition are not yet included. Thus, it is likely and expected that the total costs of the system will be higher.

In addition, the above cost estimates do not include management and maintenance costs. These can be significant, up to 1% of construction costs on an annual basis for storm surge barriers, and in the order of US$ 100,000 per kilometer per year for dikes (Jonkman et al., 2013).

It is interesting to compare this with the costs of other large scale surge suppression systems. The hurricane protection system that was (re)built after hurricane Katrina in New Orleans had a total cost of about US$ 14 billion (Frank, 2019). The total cost of the Delta Works in the Netherlands is estimated at 5.5 billion Euros (Steenepoorte, 2014). If it is assumed that these were at the 1985 price level, the present value would be more than 11 billion Euros (US$12.5 billion).

Closing discussion

This closing section discusses a number of topics and issues related to the design of the coastal barrier along the Galveston Bay in a broader context.

The design results presented above relate to the barrier features directly on the coast. Even if a coastal barrier is in place, significant hurricane-induced surges and waves can still occur in Galveston Bay. Therefore, additional measures around the bay may be required. In particular, nature-based solutions on the western shore and at Galveston Island could contribute to surge reduction and improve the ecosystem (Godfroy, Vuik, Van Berchum, & Jonkman, 2019). In parallel, additional, or alternative structural protection measures could be considered on the west side of the bay or near Houston. One example is a local storm surge barrier closer to Houston in the Ship Channel (Schlepers, 2015).

The design studies were mainly conducted between 2012 and 2019. More recently, a conceptual design of a similar coastal barrier was published by USACE and the Texas General Land Office (USACE, 2021). A full comparison is beyond the scope of this chapter, but notable differences include the following. The USACE/GLO plan includes dunes, but much lower and smaller dunes than those proposed in this chapter, thus offering lower levels of risk reduction. Also, the navigational section employs a different storm surge barrier in the form of floating sector gates (which may be vulnerable to back surge). Moreover, the USACE/GLO plan uses higher cost estimates (including for particular features such as the storm surge barrier) and includes a ring dike around Galveston and several in-bay features for local risk reduction.

The design presented in this chapter is focused on reducing flood risks for storm surges. The area is also highly vulnerable to rainfall and runoff flooding due to hurricanes, as was illustrated during hurricane Harvey in 2017. Given the multitude of interlinked hazards, an integrated plan must be developed that addresses storm surges, wind damage, and rainfall-induced flooding.

It is expected that the presented design concepts are challenging and costly, but technically feasible. One crucial aspect that needs to be addressed is the management, maintenance, and funding of the new system. In the Netherlands, the large storm surge barriers are managed by the federal government (Rijkswaterstaat, the Dutch equivalent of USACE) and dikes are mostly managed by so-called Water Authorities, which are local water management organizations.

Planning and designing such a coastal protection strategy requires a multidisciplinary approach. This includes the collaboration of specialists within civil engineering (linking geotechnical, hydraulic and structural design), but also particularly multidisciplinary explorations between architects and civil engineers (e.g., for the land barrier) and involvement of environmental experts and other disciplines. Given the long lifetime of such coastal barrier infrastructure, its planning and design ideally involve long-term urban and development strategies.

The concepts and experiences are also applicable to other coastal regions. The risk-framework presented ("Setting the scene: Risk-based evaluation of strategies" section) can be applied to any region where multiple coastal risk reduction measures are possible. For example, it has been explored in collaboration with the World Bank to inform the development of a coastal adaptation strategy for Beira, Mozambique (Van Berchum, van Ledden, Timmermans, Kwakkel, & Jonkman, 2020). Since many urbanized areas around the world are developing coastal adaptation strategies, the plans and projects for and from Texas can also inform and inspire other regions. Several metropolitan areas such as New York and Shanghai (China) are considering the implementation of storm surge barriers. Also, given the attention to more sustainable forms of coastal protection and adaptation, there is a growing interest in nature-based and hybrid solutions such as dunes and hybrid dunes.

A more overarching challenge concerns the shift from reactive to proactive: throughout history, investments in flood protection seem to be made mainly after major disasters. Examples are the construction of the Delta Works in the Netherlands after the 1953 disaster and the protection of New Orleans after hurricane Katrina in 2005. A shift to proactive planning actions and investments is required to prevent future disasters in the Netherlands, Texas, and around the world.

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