Response to
USACE Texas Coastal Study

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TABLE OF CONTENTS

Chapter 1. Summary of Key Points

Introduction

The Coastal Texas Study 2020 Draft Feasibility Report (the Report) documents a comprehensive and integrated study. Work reflected in the Report is clearly rooted in, and linked to, previous studies by the U.S. Army Corps of Engineers (USACE), the Texas General Land Office, Texas A&M University-Galveston (TAMUG) and its technical partners, Technical University of Delft (TUD) and Jackson State University (JSU), and others, and also utilizes international experience. The Report reflects a number of new and informative modeling studies and analyses. Significant improvements have been made to the recommended USACE Plan (the Plan). For example, the 7-10% reduction in tidal exchange associated with the re-designed Bolivar Roads Storm Surge Barrier is very small compared to other barriers around the world, supported by comprehensive environmental flow modelling. The decision to relocate the land barrier, moving it from behind coastal highways to the beach, is sound and evolves the Plan closer to the original Ike Dike concept. The Plan involves a combination of structural and nature-based features, including innovative concepts such as the double dune. New life-cycle dune erosion modelling provides valuable insights regarding performance of the dual dune system. The Report is much improved. The USACE has made an outstanding effort to communicate the Plan to the public through visuals and story lines. The online presentation and visualization materials are both innovative and accessible, effectively communicating the physical aspects and dimensions of Plan features.

The Plan can be and must be improved even more. Comments and recommendations provided throughout this review report are offered by TAMUG and its technical partners, TUD and JSU, in the spirit of improving the Plan to better serve stakeholders throughout the entire region. A summary of key observations and recommendations is provided below in bullet form, organized by these topics: Overall Approach to Flood Risk Reduction, Land Barrier, Gating San Luis Pass, Galveston Ring Barrier and Seawall, Other In-Bay Measures, and Bolivar Roads Storm Surge Barrier. Subsequent report chapters adopt the same topics as chapter headings, and they discuss these main points and others in more detail. The structure of this report is designed to demonstrate failure of the USACE plan to provide comprehensive protection with its coastal line of defense, because of its weak links that are covered in the next two chapters on the land barrier and San Luis Pass. In turn, the next two chapters, on the Galveston Ring Barrier and other In-Bay defenses show how the strength of the primary coastal barrier influences the In-bay lines of defense. Finally, the Bolivar Roads Surge Barrier and its costs are analyzed.

The review report also contains appendices, which provide even more supporting information. Other supporting materials are available from the TAMUG Ike Dike Home Page web site (https://www.tamug.edu/ikedike/). Specific links to other materials found on these websites are referenced in chapters and appendices.

This report has three principal authors, Mr. Bruce Ebersole of Jackson State University, Dr. Jens Figlus of Texas A&M University and Dr. Bas Jonkman of Technical University Delft. Dr. Sam Brody, Dr. Yoon Lee, Dr. Youn-Kyung Song, of Texas A&M University; Mr. Thomas Richardson and Dr. Robert Whalin of Jackson State University and Dr. Baukje Kothuis of Technical University Delft, provided guidance, technical analysis, and editorial services. Dr. Bill Merrell of Texas A&M University coordinated the response. Resumes for these individuals are in Appendix D.

Overall Approach to Flood Risk Reduction

- USACE has picked up the coastal spine concept, but made it much weaker.
- The Ike Dike concept is intended to shorten and strengthen the coastal surge defenses (like the Dutch approach); and keep water out of the bays to limit internal surges. The USACE Plan severely compromises both core objectives.
- Inclusion of 43 miles of low, weak sand dunes in the USACE Plan violates the strong coastal defense objective of the Ike Dike concept and unnecessarily allows water into the Bays.
- The USACE Plan omits a western section including a gate system at San Luis Pass; unlike the Ike Dike concept. Omission allows the surge forerunner and main surge to enter West and Galveston Bays. Every contribution to water in the Bays increases flood risk and increases the need for, and strength and cost of, all second lines of defense and nonstructural measures.
- When the USACE changed the Tentatively Selected Plan from a high levee behind the highways, in iteration 1 of the Feasibility Report, to a low weak dune at the coastline in the current USACE Plan, they failed to quantify the resulting changes in flood risk and residual damage.
- Despite an expenditure of $26.17B, the USACE Plan performs poorly in reducing flood damage for the region, decreasing average annual damages by only 60% (and by much less, 44%, for the high future sea level rise scenario).
- Even with the USACE Plan in place, average annual residual damage for the region is predicted to be $1.15B (distributed as 55% in West Bay and 45% in Galveston Bay). Average annual residual damage for the high future rate of sea level rise is 3 times higher, $3.28B.
- The region should experience even more damage than predicted because of USACE failure to fully account for their own modeling that predicts the frequent loss of dune protection through erosion and breaching of the low weak sand dunes on Galveston Island and Bolivar Peninsula.
- The USACE's own modeling shows that major hurricanes will completely destroy the dual dune system that is proposed in the USACE Plan, allowing storm surge to pour into the bays.
- The USACE has seemingly drifted far from their own National Economic Development (NED) guidelines that focus on maximizing net benefits, which for this project are primarily storm damage reduction benefits
- We recommend a renewed focus on maximizing flood risk reduction, maximizing net benefits, and increasing the benefit-cost ratio, consistent with USACE National Economic Development planning guidelines.
- The USACE Plan will put the Houston-Galveston region in a poor defensive posture for major hurricanes, now and even more so for higher future sea levels.
- The weak coastal spine in the USACE Plan leads to the need for an excessively high Galveston Ring Barrier and other in-bay defenses
- A higher level of risk reduction is needed for the coastal spine, and it can be achieved.
- A robust 17-ft Ike Dike can remedy many of the shortcomings associated with the USACE Plan. It will significantly reduce residual damage throughout the region, reduce required strength and cost of all in-bay measures, eliminate the need for many of them, reduce the elevation and cost of the Galveston Ring Barrier, enable suitable protection for the City, for future sea level, and increase the project's overall benefit-cost ratio.

- In the USACE Plan, heights of different elements comprising the coastal spine vary considerably (Bolivar Roads Barrier at 21.5 ft, lower Seawall at 21 ft, sand dunes at 14 ft). The shortest element, the Bolivar Roads Barrier, is the highest and it has water behind it. The variation seems illogical in terms of storm surge reduction and protecting life and property.
- Future sea level appears to be treated inconsistently in the design of different elements of the USACE Plan. It appears to have been considered in all gate designs. However, it is not adequately addressed in design of the Galveston Ring Barrier and Seawall improvements, or in design of the dual sand dunes. Consistency and/or clarification is needed.
- Variability in heights of different components of the coastal spine, and inconsistency in treating future sea level, leads to varying levels of protection. Transparent and effective communication of residual water levels, risk and damage for the entire region is vital and needs improvement.

Land Barrier

- The low dual dune system included in the USACE Plan is simply a refined version of the dune proposed as an environmental restoration feature in the first iteration of the Feasibility Report, except that it is now maintained for 50 years. It provides minimal flood risk reduction benefits.
- USACE storyboards show the proposed land barrier, dual dunes having 12 and 14 ft heights, will breach and overflow at 50- and 100-year conditions with significant flood risk and damage.
- Our independent modeling verifies this.
- The life-cycle beach/dune erosion modeling and analysis done by the USACE indicates that the dune elevation will remain below 12 ft for 75-80% of the time. However, the regional storm surge protection modelling was done assuming the dunes afforded 12-ft solid protection.
- Consequently, the USACE Plan underestimates storm surge entry into the Bays and underestimates residual damages.
- The USACE Plan leaves flattened and breached barrier islands in a degraded and highly vulnerable state for several years, waiting for the next scheduled renourishment (planned every 6 or 7 years), while the region hopes that both State and Federal funds (50%-50% cost sharing) will be available to pay for renourishment.
- We recommend inclusion of a provision for immediate dune renourishment whenever severe erosion occurs. Otherwise, between renourishments, areas local to the land barrier and the entire Houston/Galveston region behind it are highly vulnerable to flooding and damage.
- TUD work shows how large a natural sand dune would need to be to defend against a 100-yr storm. It would need to be 22 ft high, 300 ft wide at the base, with a 150-ft wide crest, much larger than the current dune footprint and more expensive to build and maintain.
- We recommend a fortified dune as a stronger alternative, sand covered but having a hardened core. It can occupy a similar footprint as the USACE design. It can be made higher, if desired, to better match the elevation of the Bolivar Roads Surge Barrier and Seawall.
- Preliminary work indicates that the fortified dune would be effective, from both performance and cost/benefit perspectives.
- The USACE land barrier only provides intermittent protection and periodic renourishment is contingent upon availability of funding. Adoption of a fortified dune would “lock in” protection for the life of the project, and make future project performance and regional flood risk reduction much less dependent on timely renourishment.

Gating San Luis Pass

- The USACE Plan omits a western section including a gate system at San Luis Pass; unlike the Ike Dike concept.
- Our modeling shows that not closing the pass during storm events allows fore-runner surge in the Bay as well as the main surge, which directly effects many structures on Galveston Island, the mainland north of West Bay and around Galveston Bay.
- Leaving the San Luis Pass "back door" open leads to increased flooding and inundation on Galveston Island even for relatively frequent, weaker hurricane events
- It also disallows sealing the Bay at low tide with an approaching hurricane, to minimize in-Bay surge.
- Every contribution to water height in the Bay increases the surge and thus increases the need for and strength of the in-Bay lines of defense.
- The USACE presents no technical analysis to support not gating San Luis Pass, instead relying on hand-waving and unsupported generalities.
- The stated goal for the USACE Plan is to "promote a resilient and sustainable economy by reducing the risk of storm damage to residential structures, industries, and businesses critical to the Nation's economy."
- We recommend that the USACE conduct a thorough analysis of the benefits and costs associated with a western section of the coastal spine, which includes a gate at San Luis Pass.
- Benefits include direct reduction in damage as well as cost avoidances that arise from being able to reduce design water levels and wave conditions for all in-bay second lines of defense and non-structural measures, which in turn reduces the required extent, strength, height and cost of all in-bay measures.

Galveston Ring Barrier and Seawall

- It is crucial that the pump stations, other features, and operations for evacuating water from the Ring Barrier interior be designed to accommodate overtopping of the Galveston Seawall and the Ring Barrier in the event the design conditions are exceeded. While elevations can be designed using a 100-yr design standard, all structural elements must be resilient, designed to remain robust and fully functional, if design overtopping conditions are exceeded. Pumps should be designed using a higher design standard than a 100-yr standard, something like what the Dutch adopt when human life and safety is at risk. Pumps stations must be designed with resiliency and redundancy to reduce their risk of failure to very low levels. This is critical for avoiding loss of life. This entire subject is inadequately addressed in the USACE Plan.
- This is a complex and very difficult project, with both major flood threats increasing – sea level rise and rainfall rates. Coupled rainfall and surge hazards during hurricanes must be effectively considered in the design.
- Present plans call for a wall for protection; this will be obtrusive and divisive. We recommend consideration of a design approach that incorporates city functions into the protection using urban landscape architecture best practices – fewer walls; and consideration of using nature-based features to lower wall elevations or replace walls.
- Much of that protection to accommodate rising sea level probably won't be needed for a number of years. It might be best to take an adaptive management approach that incorporates

actual rates of increase of threats, changes in the built and natural environment, and new technologies in an evolving protection scheme.

- Raising the Galveston Ring Barrier to an elevation of 18 ft, which is recommended in the USACE Plan to accommodate future sea level, is strongly opposed by many local stakeholders.
- Implementation of a strong robust 17-ft Ike Dike concept will lower 100-yr design water levels at the Ring Barrier by 3 to 4 ft, compared to the USACE Plan. Such reductions will greatly improve Ring Barrier design and acceptability, lower its cost significantly, and, it would render a 13 or 14-ft Ring Barrier elevation suitable for accommodating the intermediate future sea level rise scenario.
- The 100-yr design water level, wave and overtopping conditions vary around the Ring Barrier perimeter. Yet, the proposed elevation of the Ring Barrier is a constant 14 ft. We recommend modifying the barrier height as needed to achieve consistency in application of the overtopping design standard, particularly lowering wall elevation in areas sheltered by Pelican Island that have reduced overtopping threats, particularly near the historic downtown area.
- We recommend carefully designing transitions between the lower Ring Barrier and the higher (21-ft) Seawall, avoiding over/under design and potential vulnerabilities (low spots).
- We concur with raising the Seawall to a uniform elevation, eliminating local vulnerabilities.
- Neither the 14-ft Ring Barrier nor the 21-ft Seawall in the USACE Plan appears to adequately account for future sea level rise. Accommodations for future sea level should be planned and designed, and the plan clearly communicated along with the residual risk that remains for the City.
- The City now has active and planned drainage improvements. We are not convinced that these improvements have been adequately interfaced to the USACE Plan for pumping and for delivery of water to the pump stations.
- Adequacy and feasibility of the USACE Plan for using underground conduits to convey water to the location of pump stations has not been demonstrated.
- We recommend that the Seawall elevation be slightly higher (1 or 2 ft) than the top elevations of the adjacent land barrier and Bolivar Roads Surge Barrier, to help divert storm surge away from the City. This is not the case in the USACE Plan.

Other In-Bay Measures

- With such high residual damage for the present USACE Plan, there are probably other in-bay measures in Galveston and West Bays that are cost-effective, but are not included in the Plan.
- No clear rationale is apparent for evaluating and selecting areas for implementation of second lines of defense and non-structural measures to reduce the high residual damage further. Selection of measures included in the Plan appears to be arbitrary, focused on the western side of Galveston Bay, apparently without consideration of other areas that also have significant residual damage, particularly those in West Bay where 55% of the residual damage occurs.
- The short extent of both the Clear Lake and Dickinson wall/gate structures appears to make them vulnerable to flanking by the storm surge. We recommend careful examination and assessment of cost and benefits of mitigation. The effect of storm surge flanking on pump requirements should also be considered and examined.
- JSU and USACE surge modeling results both suggest an overland pathway, near the Shoreacres community, for storm surge to enter the Clear Lake region. This pathway is different from the

one addressed by the wall/gate system at the entrance to Clear Lake. We believe this pathway is a cause for the high residual damage that remains in this area. We recommend careful examination and assessment of cost and benefits of measures to mitigate this pathway and reduce residual damage further.

- JSU and USACE surge modeling results both suggest that the high residual damage in the Texas City area is due to flanking around the southwestern terminus of the Texas City Levee. We recommend careful examination and assessment of cost and benefits of measures to mitigate this flanking and reduce residual damage further.
- The USACE Plan actually <u>induces</u> significant damage in eastern West Bay and, to a lesser degree, in the eastern half of Bolivar Peninsula. We recommend careful examination and assessment of cost and benefits of measures to mitigate the induced damage in both areas, and drive down residual damage in eastern West Bay.
- As is the case for the Galveston Ring Barrier, improving the coastal spine by fully implementing something like the 17-ft Ike Dike concept would help lower water levels everywhere in the Bays, reduce the cost of all other in-bay measures, and eliminate the need for many of them.
- We encourage design and placement of nature based features so that they contribute to shore protection and flood risk reduction. It seems that marshes might be able to reduce wave energy on the bay sides of Galveston Island and Bolivar Peninsula and perhaps areas along the north shore of West Bay, reducing residual risk. Marshes or other nature-based measures might help to partially mitigate damage induced by the USACE Plan.

Bolivar Roads Storm Surge Barrier

- USACE is commended for working with the international ISTORM storm surge barrier group and producing a greatly improved design.
- The proposed floating sector gates are subject to failure from a negative head caused by back surge from the bay side. In this particular coastal setting, there is great potential for large negative heads because of the large size and shallowness of Galveston Bay and the strength of extreme hurricane winds. This critical design issue has not been adequately addressed.
- We recommend consideration of barge gates as the principal navigation gates to circumvent the negative head design issue. Barge gates also would allow for a self-opening design during back surge events.
- Two main channels with navigational gates are proposed, whereas one might be sufficient.
- The cost estimate, $13.8B, seems very high, much higher than international experience suggests. We are concerned that the high estimate adversely skews the overall cost estimate for the project, and led to limited consideration of other means for reducing residual damage.

Chapter 2. The USACE Coastal Spine – A Weakened Ike Dike

Comparison of the Ike Dike Concept and the USACE Plan

Figure 2-1 shows the current Ike Dike concept, an idea that was originally proposed by Dr. William Merrell, Texas A&M University-Galveston (TAMUG), shortly after Hurricane Ike severely damaged the Houston-Galveston region in 2008 (Houston Chronicle, 2009). The Ike Dike concept is comprised of three sections. The middle section, positioned at the shoreline, extends from High Island to the western end of Galveston Island. The eastern section turns inland at High Island. The western section, also positioned at the shoreline, extends from the western end of Galveston Island to Freeport, Texas, where it ties into the existing system of hurricane protection levees there. The Ike Dike includes a large storm surge barrier and gate system that spans Bolivar Roads pass; and it includes a small storm surge barrier and gate system that spans San Luis Pass.

Jackson State University, JSU (2018), evaluated the storm surge reduction achieved with a 17-ft high Ike Dike and found that a 17-ft crest elevation is quite effective in providing substantial reduction in surge levels for the entire region (shown in a later section). JSU (2018) research showed that middle and western sections are important elements for reducing flood risk throughout the region that lies behind the coastal spine. Research showed that the western section is much more important than the eastern section in reducing surge levels. The eastern section primarily provides benefits for the less populated eastern side of Galveston Bay. Current thinking is that the eastern section is probably not cost effective.

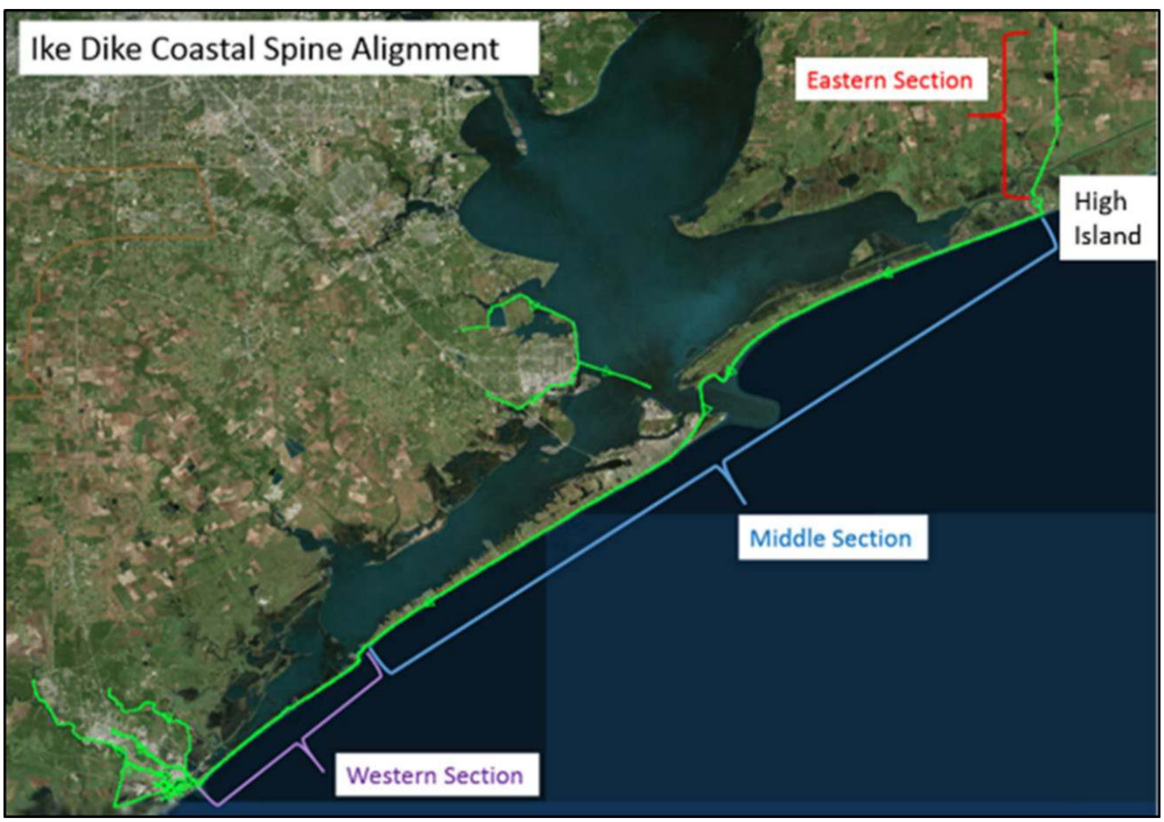

Figure 2-1. Schematic of the footprint for the Ike Dike coastal spine concept.

Figure 2-2, taken from USACE (2020), shows the footprint of the recommended USACE Plan. The Plan is comprised of multiple lines of defense, a sound strategy for reducing flood risk. The first line of defense, a coastal spine positioned at the shoreline, extends from High Island to the western end of Galveston Island. The footprint of the USACE coastal spine is now nearly the same as the middle section of the Ike Dike concept. In the USACE Plan, land barrier segments of the coastal spine, on Galveston Island and Bolivar Peninsula, consist of low dual sand dunes (heights of 12 and 14 ft). Like the Ike Dike, the USACE Plan includes a large storm surge barrier and gate system that spans Bolivar Roads Pass (elevation of 21.5 ft). The USACE Plan has no western section or gate system at San Luis Pass. The Plan raises the Galveston Seawall to 21 ft. The Plan includes multiple in-bay measures to reduce residual flood-induced damage further. In-bay measures consist of the Galveston Ring Barrier that encircles the City of Galveston and joins the Seawall, short storm surge wall/gate systems at the entrance channels leading to both the Clear Lake and Dickinson areas, and non-structural measures along the western side of Galveston Bay in the crosshatched areas shown in Figure 2-2. It is important to note that the strength of the first line of defense, the coastal spine, influences the required extent, strength, and cost for all in-bay measures.

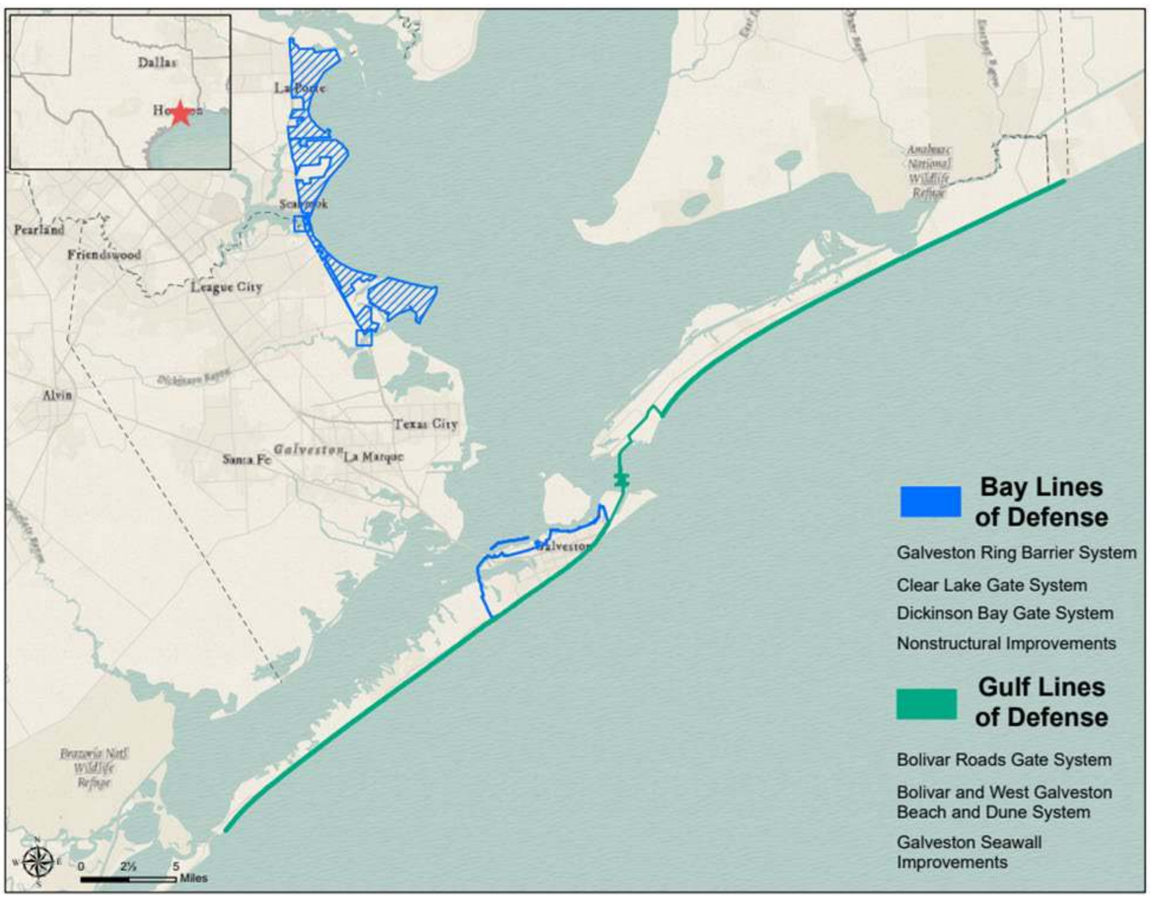

Figure 2-2. Schematic of the footprint for the USACE Plan

USACE has picked up the Ike Dike concept but made it much weaker, to the point that the land barrier in the USACE Plan provides minimal benefit in reducing damage and flood risk. The Ike Dike concept is intended to shorten and strengthen the coastal surge defenses (like the Dutch approach); and keep water out of the bays to limit internal surges. The USACE Plan severely compromises both core objectives; and it does so in two ways: 1) by adopting a low easily erodible sand dune system for the land barrier on Galveston Island and Bolivar Peninsula, and 2) by omitting the western section of the coastal spine, including the San Luis Pass gate system, which the Ike Dike concept includes. Even with the USACE Plan considerable residual damage and risk remains throughout the region that lies behind the coastal spine. In contrast, a robust Ike Dike, with a strong land barrier and a western section having a gate system at San Luis Pass, substantially reduces residual damage and risk throughout the entire region, compared to the USACE Plan.

Weak Land Barrier in the USACE Plan

Both the beach/dune erosion modeling described in USACE (2020) and the modeling and analyses presented in the next chapter, Chapter 3, show that the low dual dune system in the USACE Plan performs poorly for hurricanes, even weak hurricanes. For example, USACE beach/dune erosion modeling showed that the proposed dual dune system is flattened completely in their simulation of Hurricane Ike, which produced a measured peak surge level of 11 ft NAVD88 at the Galveston Pleasure Pier (lower than the heights of the 12- and 14-ft dunes). The stage-frequency curve shown in Figure 2-22 of Appendix D to USACE (2020) shows that a peak surge of 11 ft corresponds to a return period of 30 years.

The proposed dual dune system performs poorly even for weaker non-tropical and tropical storms. As stated in USACE (2020), “Non-tropical storms were shown to produce only slight profile responses but were frequent so the total impact on profile evolution was significant,” and “Tropical Cyclones had dramatic effect on the dune with near complete destruction if the dune crest was submerged,” and “the dune fails quickly once overtopping begins, leaving the upland area exposed to storm surge and direct wave impact.” It is notable that the proposed frequency of dune renourishment in the USACE Plan, which is planned every 6 or 7 years and is based upon the calculated frequency of dune flattening, is identical to the recurrence rate of what the USACE defines as “intermediate” tropical cyclones, which in essence are relatively weak Category 1 and 2 strength hurricanes.

Dune destruction enables storm surge to enter Galveston and/or West Bays, increasing internal surge generation and exacerbating flooding throughout the entire region. Major hurricanes, which have a recurrence rate of once every 9 years, on average, according to the USACE Report, will quickly and completely devastate the dunes and likely lead to breaching of the barrier islands much like what occurred during Hurricane Ike. For major hurricanes, storm surge will pour into the bays, causing considerable flooding and damage, much of which can be avoided with a more robust and stronger land barrier. Chapter 3 discusses use of a fortified dune to address this weakness of the USACE Plan.

To compound the poor performance of the USACE land barrier, once a storm flattens the dunes, or worse, breaches the barrier islands, the USACE Plan contains no provision for emergency dune and barrier island repair. Instead, the heavily damaged dune system and degraded barrier island will remain in this state until the next scheduled renourishment, which could be as much as 5 or 6 years in the future and possibly more if funding from both the State and Federal governments (a 50/50 cost share) is not available to perform renourishment in a timely manner. The periodic dune renourishment proposed in the USACE Plan will leave the entire region vulnerable to severe flooding if another hurricane strikes during the same hurricane season or anytime in the succeeding years before completion of the next renourishment. A strong and resilient land barrier, comprised of a fortified dune of the type proposed in Chapter 3, avoids this vulnerability.

Omitting the Western Section of the Coastal Spine

Unlike the Ike Dike concept, the coastal spine in the USACE Plan notably lacks continuity between the hurricane protection levee system at Freeport and the west end of Galveston Island, leaving open a "back door" that enables surge propagation into both West and Galveston Bays. Omitting the western section of the coastal spine, which includes a gate system at San Luis Pass, allows the hurricane surge forerunner to propagate through San Luis Pass, into West Bay, and then into Galveston Bay, albeit with a reduced amplitude. Omission also enables the main surge to flank the western end of the USACE coastal spine, first through San Luis Pass and then over an inundated Follets Island, enter West Bay, and then to a lesser degree from West Bay into Galveston Bay. Every contribution to water in the Bays increases flood risk and damage. The critical role of the western section, and the consequences of omitting it, are explained further and discussed in more detail in Chapter 4. Several examples of increased inundation and damage arising from omission of the western section, in both Bays, are presented graphically in Chapter 4. We recommend a thorough, quantitative examination of the cost and benefits of providing a continuous first line of defense in this region, including cost avoidance/savings for the Galveston Ring Barrier and all other in-bay measures.

USACE cites a number of reasons for not including a gate system at San Luis Pass. One reason cited is that there is little additional flood damage and risk associated with leaving San Luis Pass open. This claim is contradicted by information provided in USACE (2020); 55% of the $1.15B in average annual residual damage occurs in West Bay, much of which is due to omission of the western section, some due to the low weak land barrier. Related to the first reason, USACE claims that the water exchange between West Bay and Galveston Bay is only 3-5%, with the implication that this magnitude is too small to make a difference in Galveston Bay. It is unclear if this magnitude of exchange refers to astronomical tide-induced exchange or to forerunner-induced exchange. Tidal exchange will be different from exchange for the forerunner; the latter has a much longer "period" and does not reverse direction every 24 hours like the tide does. Also, water exchange relates to filling, but wind compounds the effect of filling, setting down one side and setting up the other. During hurricanes, we expect that the exchange between the two bays depends upon forerunner amplitude, the main surge hydrograph, local winds, and sea level. JSU research indicates that the propagation of the surge forerunner into Galveston Bay, via West Bay, is exacerbated by rising sea level. Damping of the forerunner and main surge that propagate through an open San Luis Pass does occur, and is discussed in Chapter 4. However, even if propagation from West Bay into Galveston Bay is such that peak surge in Galveston Bay is only increased by 1 or 2 ft, this change can cause or exacerbate flooding and damage, as demonstrated in Chapter 4.

The western section, and a gate at San Luis Pass, has been dismissed by the USACE with no rigorous economic analysis of cost and benefits to support the decision. Engagement with other modelers on this topic, and their concurrence with the USACE position, are cited in USACE (2020) as a justification for omitting the western section; however, none of those other modelers has done a rigorous benefit-cost analysis either. Appendix B provides a simple analysis of the cost effectiveness of implementing the full Ike Dike concept, including the western section and a robust land barrier having a fortified dune. Results from the analysis presented in Appendix B suggest that full Ike Dike implementation is cost effective, and it will increase the benefit-cost ratio for the entire project.

A second reason cited is the USACE claim that San Luis Pass is the last natural inlet in Texas, seemingly one that is unaffected by human intervention. We believe the Pass has been influenced by a number of engineering activities: 1) shoaling induced by bridge construction, and 2) by construction and maintenance of the navigation channel and jetty system at Bolivar Roads, and subsequent formation of tidal shoals, which have altered alongshore transport of sand toward the west and toward the Pass for some time. We expect that the very large volume of sand to be placed on Galveston Island as part of the USACE Plan, much of which will be transported to the west, will also strongly influence the Pass.

A third reason cited is the perceived adverse impact that a gate system would have on the environment. To date, the USACE has done no serious rigorous analyses to quantify the environmental impact of adding a gate system at San Luis Pass, and no specific environmental impacts have been identified. The San Luis Pass gate has been dismissed for environmental reasons with simple hand waving. We recommend that a rigorous technical analysis be done of the environmental impact of the San Luis Pass gate system, as part of an overall evaluation of the Ike Dike's western section. The USACE has undertaken rigorous environmental flow modeling and analyses to examine the environmental impact of the gate system at Bolivar Roads; and successfully designed a gate system that seems to have minimal impact on the environment. We see no reason why the same cannot be done at San Luis Pass. It appears that the modeling tools and analysis techniques required to do a rigorous analysis have already been created to facilitate the investigation of environmental impacts associated with the Bolivar Roads Surge Barrier.

One of the core objectives of the Ike Dike concept is to minimize the amount of water in the bays at the time of hurricane landfall, which reduces the potential for internal surges. Both large shallow bays, West Bay and Galveston Bay, are highly conducive to internal surge generation. Gating Bolivar Roads Pass enables partial sealing of the bays (it is the main source of filling). Gating San Luis Pass allows complete sealing of the bays. In light of uncertainties surrounding the hurricane surge forerunner and its prediction (discussed in Chapter 4) and the importance of keeping the forerunner and main surge out of the bays, we recommend inclusion of the western section and gate system at San Luis Pass in the USACE Plan.

Sealing the bays early is essential for minimizing the amount of internally-generated storm surge. Referring to the Bolivar Roads surge gates, the USACE (2020) states, "The gate operations will be dependent on the intensity, track and orientation of the land falling storm which will dictate the trigger condition (e.g., 3m TWL) of gate closings." Waiting until the total water level (TWL) reaches nearly 10 ft before closing the gates would likely be disastrous and lead to severe flooding for the region. Ten additional feet of water inside the bays will lead to much larger internal surges. The hurricane surge forerunner will be extremely important in the decision of when to close the gates. It will be critically important to close the gates while the surge forerunner amplitude is small and probably at low tide.

Performance of the USACE Coastal Spine –Damage and Risk Reduction

The USACE coastal spine provides limited protection for the region (less than 50 years). The stage frequency curve in Figure 2-22 of Appendix D to the USACE (2020) report shows that 50-yr and 100-yr water levels just offshore of Galveston are 13 and 16.5 ft, respectively, for present sea level (compared to dune elevations of 12 and 14 ft for the USACE land barrier). As illustrated below in Figure 2-3, which shows inundation maps without and with the USACE Plan, the proposed weak land barrier will breach and overflow at 50- and 100-year conditions, resulting in significant inundation, damage and risk. Both Galveston Island (the portion that lies outside the Ring Barrier) and Bolivar Peninsula are completely inundated, as is the entire West Bay north shore and multiple areas of the Galveston Bay periphery.

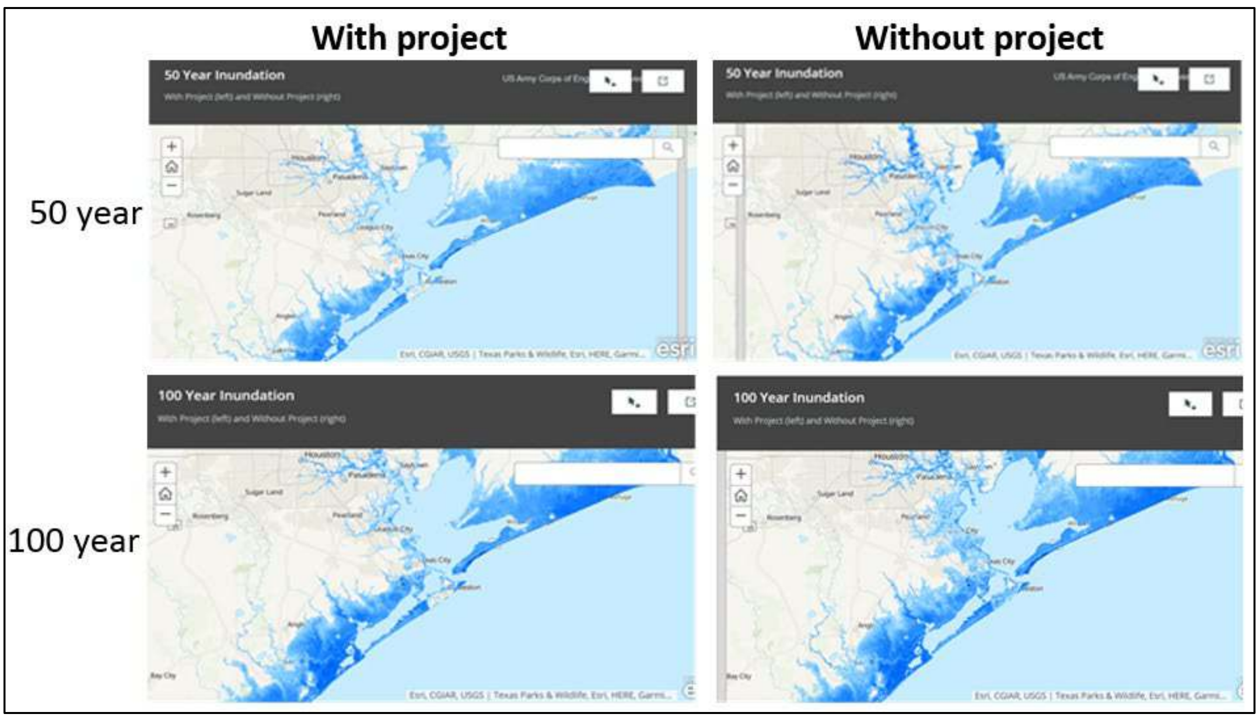

Figure 2-3. Inundation associated with the USACE Plan for 50-yr and 100-yr events, and for the intermediate sea level rise scenario (images extracted from the Storm Surge Modeling StoryMap. Coastal Texas Study web page)

Poor performance of the low dual dune land barriers in the USACE coastal spine, and omission of the western section, leads to poor performance in reducing damage and flood risk. Despite an expenditure of $26.17B, the USACE Plan decreases average annual damages by only 60% for the intermediate sea level rise scenario. Even with the USACE Plan in place, residual average annual damage is predicted to be very high, $1.15B (split this way: 55% in West Bay and 45% in Galveston Bay).

For the high future sea level rise scenario, the Plan performs even more poorly, decreasing average annual damages by only 44%. For this high sea level rise scenario, the predicted average annual residual damage is nearly 3 times as high, $3.28B, as damage for the intermediate sea level rise scenario. The USACE Plan fails to position the entire region in a sound protective posture, should the intermediate or high future rates of sea level rise occur. A higher level of protection is needed, which achieves greater risk reduction for both present sea level and possible higher future sea levels. A stronger more robust Ike Dike can provide the higher level of protection.

The very high amounts of residual damage are a significant shortcoming for such a major investment. However, the region should experience even more damage than predicted because of USACE failure to fully account for their own modeling that predicts the frequent loss of dune protection through erosion and breaching of the low weak sand dunes on Galveston Island and Bolivar Peninsula. In the with-project storm surge modeling, the dual sand dune system is represented as a solid barrier having an elevation of 12 ft. However, results of the USACE life cycle beach/dune response modeling in Annex 1 to Appendix D of USACE (2020) indicate that the dune is below 12 ft for 75%-80% of the time.

Once this flaw is corrected in the surge modeling, we expect even higher residual damages throughout the entire region and a decrease in the project's benefit-cost ratio. Because of the flaw, all second lines of defense and nonstructural measures are probably under-designed; and their costs are probably underestimated. A strong Ike Dike can substantially reduce residual damages throughout the region; improve the project's benefit-cost ratio, and lower costs for all in-bay measures including the Ring Barrier.

For major hurricanes, in essence, the USACE Plan stops only half the surge, the half that propagates through Bolivar Roads Pass; but it allows half the surge to enter into the bays over the degraded and breached barrier islands and by flanking the western end of the coastal spine. The USACE Plan fails to meet the crucial objective of keeping water out of the shallow bays, leading to much higher in-Bay surge. Its performance lies somewhere between the Ike Dike coastal spine concept and previously eliminated, ill-conceived alternatives that sought to defend against the surge by locating the first line of defense inside Galveston Bay. The weak first line of defense in the USACE Plan means that the second lines of defense and non-structural measures inside the bays must be more widespread, stronger and higher, and therefore more costly.

Loss of Focus on Reducing Damage and Flood Risk

In the latest iteration of the USACE Feasibility Study, the strength of the land barrier in the USACE Plan decreased dramatically. The Plan Formulation Appendix A in USACE (2020) discusses this major change, and states:

> *4.3.1 Levee along West Galveston and Bolivar Levee*
> *The levee proposed along West Galveston and Bolivar peninsula provided an engineered barrier to prevent storm surge from entering the Bay over land. Public comment indicated that the roadway access issues were unfavorable, the real estate impacts were disruptive, and the views would be unacceptably changed. Many expressed dissatisfaction that the impacts would be borne by the residents and businesses on the island and peninsula without reducing their storm surge risk. Many commenters also expressed that they are aware of the risks of development on a barrier island or peninsula, and accept the risk of storm damage over the levee. In response, the Team found that the levee was unimplementable and it was removed from the recommendation.*
>
> *4.3.2 Beach and Dune Restoration (G5)*
> *The beach and dune restoration feature proposed along the Gulf on West Galveston and Bolivar Peninsula was justified for inclusion within the ER purpose. It restored the coastal habitat that had lost sediment to years of coastal forces on the Gulf side and hardened features, yards, structures and roadways. Once the levee, was found to be unacceptable, the beach and dune restoration was refined to include taller dunes and wider berms to increase the risk reduction it provides. The beach feature does not provide a comparable scale of risk reduction as compared to the levee, but is placed gulfward of all structures, and creates fewer community impacts. The larger beach feature also sustains the barrier features and supports the function of the Bolivar Roads Gate System.*

Clearly, preferences by some public commenters and other motivations have adversely reshaped this project in critical ways. Engineered coastal levees (18 ft high on Bolivar Peninsula and 17 ft high on Galveston Island) were dropped from the project. They were replaced with a lower and much weaker natural sand dune system (12 and 14 ft high dunes on both Galveston Island and Bolivar Peninsula) that performs poorly in reducing damage and flood risk. The text above acknowledges that the low dune system "does not provide a comparable scale of risk reduction as compared to the levee;" however, no thorough quantitative evaluation of the adverse impact of this major change on flood damage reduction throughout the region was done. We recommend that such an analysis be done, and that results are clearly communicated to all regional stakeholders.

It appears that the nature of the USACE Plan has fundamentally changed, from a regional flood risk reduction project with local ecosystem restoration features to more of a regional ecosystem restoration project with local flood risk reduction features. The concept of a strong regional-scale coastal spine as a first line of defense to reduce flood damage has been abandoned. As indicated in USACE (2020), the low dual dune system included in the USACE Plan is simply a refined version of the dune proposed as an environmental restoration feature (G5) in the first iteration of the Feasibility Study, but now maintained for the 50-yr economic life of the project at a total fully funded cost of $8.4B. It is quite clear that the land barrier in the USACE Plan is primarily an ecosystem restoration feature, having minimal benefit in reducing damage and flood risk for the region. Omission of an emergency dune repair component in the USACE Plan is another clear indicator that the proposed beach/dune system is little more than a long-term ecosystem restoration measure, and not an effective flood risk reduction element of a coastal spine.

In light of the very high residual damage and risk associated with the USACE Plan, the apparent shift in focus for the important land barrier, we recommend a return to trying to minimize flood risk, and maximize net benefits and the benefit-cost ratio, consistent with USACE National Economic Development guidelines. Stakeholder preferences are certainly important. However, compromise will be required because of the regional nature of this project, and the overriding importance of the coastal spine in reducing flood risk for everyone and everything behind it.

Inconsistencies in the Applied Design Standard

It appears that other preferences and motivations also have led to compromises and inconsistencies in the design standard. The USACE (2020) Design Appendix D states "The criteria used for conceptual design of the systems and crest elevations is fundamentally based on damage overtopping limit state with annual exceedance probability of 1%." The Appendix states that the 1% AEP overtopping threshold is used along with the 10-yr and 25-yr rainfall rates to conduct drainage analyses and determine pump capacities. An intermediate rate of sea level rise is included as part of the design standard. However, for several proposed elements of the USACE Plan, a lower design standard has been used. For example, the elevation of the dual dune system (14 ft) is set far below (probably 10 ft, or more, lower) than the elevation that would adhere to the design standard It appears that design of improvements to the Galveston Seawall has not fully accounted for future sea level, which impacts pump selection and project performance. The elevation of the Galveston Ring Barrier (14 ft) was selected in an effort to address concerns with stick-up heights for the proposed floodwalls. Elevation selection and pump design for the Ring Barrier was done using present sea level conditions, not the intermediate se level rise scenario as specified in the design standard. Adherence to the stated design standard would result in an 18-ft elevation and greater stick-up heights. Pump station capacities at Clear Lake and Dickinson Bay were scaled back from 25-yr (+ 30%) rates to 10-yr rainfall rates to reduce the size of the pump station footprints. The use of different and inconsistent design approaches/standards for different project components is of concern, and can lead to different levels of protection and uneven performance.

Varying Heights of USACE Coastal Spine Elements

In the USACE coastal spine, heights of different elements comprising the spine vary considerably (Bolivar Roads Storm Surge Barrier at 21.5 ft, slightly lower Seawall at 21 ft, much lower sand dunes at 14 ft). The shortest element, the Bolivar Roads Surge Barrier which is about 2 miles in length, has the highest elevation. The Seawall, which is approximately 7 miles long and protects the City of Galveston is lower. The longest element by far, 43 miles of land barrier, has the lowest elevation, and is much lower than the other elements. The variation seems illogical in terms of storm surge reduction and protecting life and property. We recommend much more consistency in elevation for all elements of the coastal spine, increasing the height of the land barrier, thereby avoiding weaknesses in the level of protection provided by the critical first line of defense.

The crest elevations of the Bolivar Roads Surge Barrier and the land barriers should complement the elevation of the Galveston Seawall. We recommend that the crest elevations of both the gate system and land barriers be less than the elevation of the Galveston Seawall, by 1 or 2 ft. In the event of storm surge that approaches the crest elevation of the Seawall, a Bolivar Roads Surge Barrier and land barriers that are lower than the Seawall help divert water away from the Seawall. This diversion in turn helps reduce the volume of overtopping that enters the City, and reduces the potential for damage. A Bolivar Roads Surge Barrier that is higher than the Seawall, as is presently the case in the USACE Plan, would tend to divert water toward the City, which is undesirable. The Bolivar Roads Barrier can be overtopped without much harm.

Variability in heights of different components of the coastal spine, and inconsistency in treating future sea level, leads to varying levels of protection. Transparent and effective communication of residual water levels, risk and damage for the entire region is essential, and is discussed more in a later section.

A Better Approach – a Robust Ike Dike

From a regional perspective, a higher level of protection is needed from the coastal spine, the first line of defense; and it can be achieved in a cost effective manner. A robust Ike Dike, comprised of a fortified sand dune, enhanced with a solid core, and gate systems at Bolivar Roads and San Luis Passes can remedy many of the shortcomings associated with the USACE coastal spine. Implementation of the Ike Dike concept is referred to here as the 17-ft Ike Dike; it has been the subject of extensive research that is documented in the JSU (2018) report and elsewhere in this report.

Figures 2-4 and 2-5 show peak storm surge maps (i.e., maps of maximum water surface elevation) for the 100-yr proxy storm, Storm 033, from the JSU research. Storm 033 is a hypothetical major hurricane that produces peak surges that best replicate 100-yr statistical values along the west side of Galveston Bay, for existing conditions. Results shown in both figures are for a higher future sea level, +3.31 ft NAVD88, the value used in JSU research. Note that the USACE uses a very similar future sea level of +3.46 ft NAVD88 to represent their intermediate scenario for future sea level rise. Figure 2-4 shows results for Storm 033 and the future without-project condition. Figure 2-5 shows results for Storm 033, for a future with-project condition, the 17-ft Ike Dike. Peak surge results shown in both figures do not reflect a snap-shot in time during the hurricane. Rather, they reflect the maximum storm surge value that is computed at each computational point of the surge model domain, during the hurricane simulation, without regard for when the maximum surge value occurred during the simulation.

The substantial reduction in peak storm surge achieved with the 17-ft Ike Dike is seen by comparing the peak surge maps in Figures 2-4 and 2-5. The 17-ft Ike Dike reduces peak surge levels by 8 to 10 ft all along the western side of Galveston Bay and into the upper Houston Ship Channel. Reductions in West Bay range from 6 to 8 ft throughout most of the Bay.

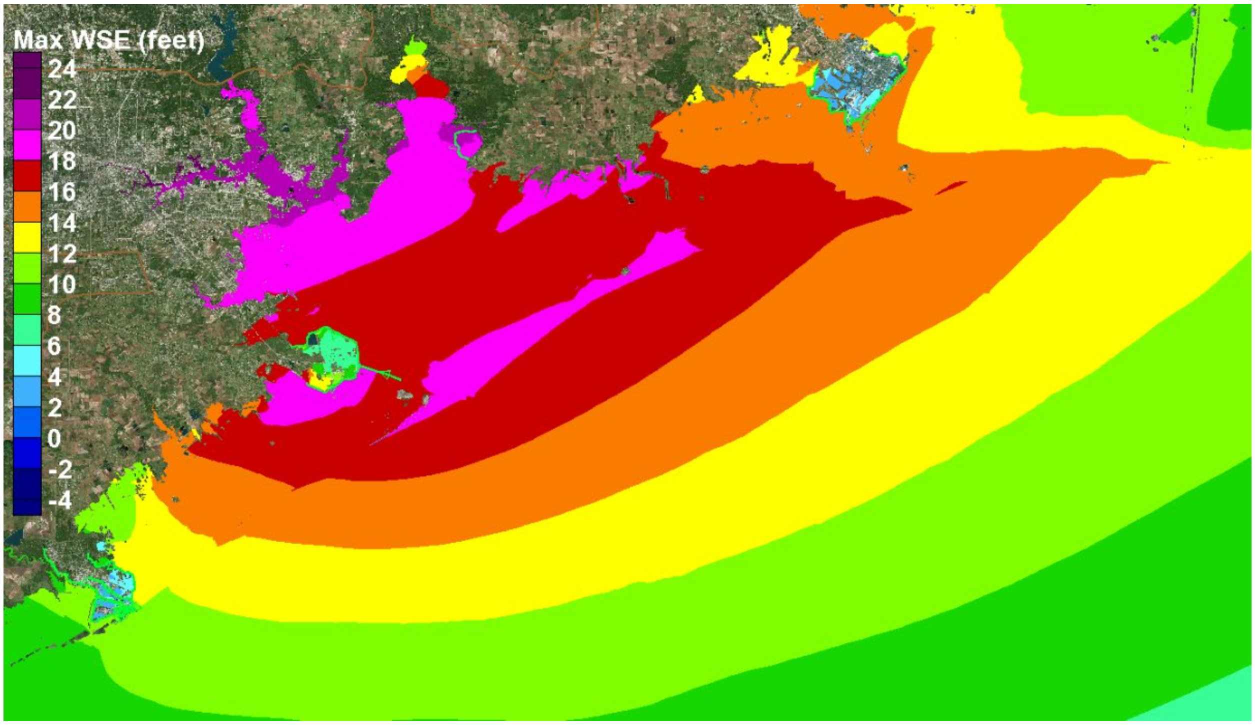

Figure 2-4. Maximum water surface elevation field (in feet, NAVD88) for the future sea level scenario (SLR1, +3.31 ft NAVD88). Without-project conditions for Storm 033 (100-yr proxy).

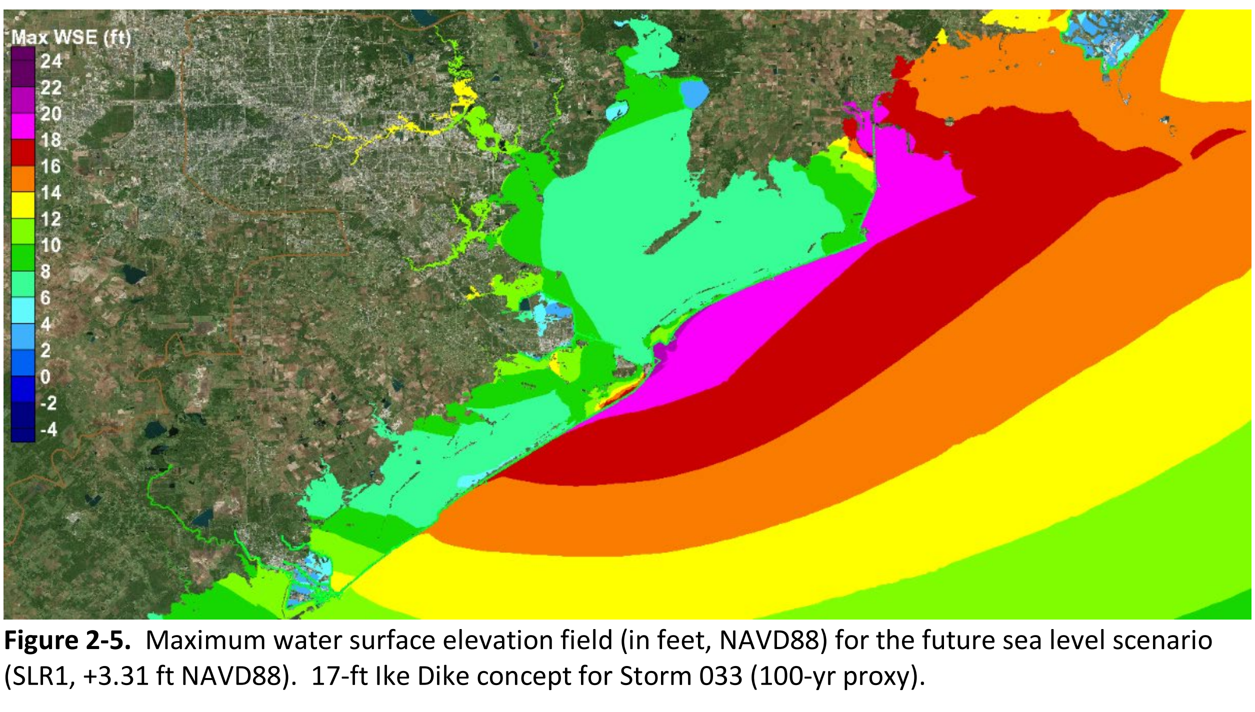

Figure 2-5. Maximum water surface elevation field (in feet, NAVD88) for the future sea level scenario (SLR1, +3.31 ft NAVD88). 17-ft Ike Dike concept for Storm 033 (100-yr proxy).

As seen in Figure 2-5, peak surge on the Gulf side of the Galveston Seawall ranges from 18 to 20 ft. Evidence that this magnitude of peak surge exceeds the 17-ft elevation of the Seawall, and the resulting steady overflow that occurs, is evidenced in Figure 2-5 by the high peak surge values immediately behind the Seawall in the City of Galveston. With improvements proposed by the USACE, the Seawall will be raised to an elevation of 21 ft. If the Ike Dike simulation for Storm 033 had included a 21-ft high Seawall, overflow of the Seawall into the City of Galveston would have been eliminated. Had a 21-ft Seawall been included in the simulation, we expect that results would show a peak surge of 8 to 9 on the bay side of the City of Galveston, a reduction of 9 to 10 ft.

The peak surge for the 100-yr proxy storm on the Gulf side of Galveston, and future sea level, 18 to 20 ft, is nearly the same as the future 100-yr water level at the same location for the USACE Plan, 18.6 ft (estimated from information provided in the USACE Feasibility Report). In light of the similarities in future sea level and open cost 100-yr peak surge values, comparisons can be made between the 100-yr proxy storm results for the 17-ft Ike Dike and 100-yr design water levels for the USACE Plan provided in USACE (2020). For the USACE Plan, future with-project 100-yr water levels on the bay side of the City of Galveston range from approximately 10.3 to 12.3 for present sea level and 12.4 to 14.4 ft for future sea level. As discussed above, we expect values for the 17-ft Ike Dike to be 8 to 9 ft, which is 3 to 4 feet lower than the 100-yr values for the USACE Plan. For the USACE Plan, future with-project 100-yr water levels at the entrances to Dickinson and Clear Lake are 12.8 and 13.5 ft, respectively. Based on results shown in Figure 2-5, we expect values for the 17-ft Ike Dike to be approximately 10 ft, roughly 3 ft lower than the USACE 100-yr water levels.

JSU research indicates that a 17-ft Ike Dike will reduce 100-yr surge levels by 3 to 4 feet in Galveston Bay, and by 3 to 6 ft in West Bay, compared to the USACE Plan. It is important to note that once the flaw in the USACE storm surge modeling is corrected, The USACE design water levels inside the bay will increase, and the improvement offered by the Ike Dike concept will increase as well. The 17-ft Ike Dike is far superior to the USACE Plan in reducing flood risk for the entire region. It will significantly reduce residual damages throughout the region, along the peripheries of both bays. It will reduce the extent of, and the required height and strength and cost of, all in-bay measures, eliminate the need for many of them, reduce the required elevation and cost of the Galveston Ring Barrier (discussed in Chapter 5) and the wall/gate systems at Clear Lake and Dickinson. We expect that a 17-ft Ike Dike will enable compliance with the 100-yr design standard (and for future sea level) for a Galveston Ring Barrier having an elevation of 13-14 ft. The 17-ft Ike Dike will not met the 100-yr design standard for the land barrier (an elevation approaching 24 or 25 ft would be required to do so for the future intermediate sea level rise scenario), but it represents a compromise to address preferences for a lower barrier. With a foot or two of sand cover over a 17-ft solid core, the crest elevation is roughly equal to the current base flood elevation (18-19 ft) for FEMA VE Zones located adjacent to the shorelines of Galveston Island and Bolivar Peninsula. It is much more consistent in elevation and protection level with the 21-ft Seawall than the 12 and 14-ft dunes in the USACE Plan.

We recommend lowering the height of the Bolivar Roads Storm Surge Barrier to 19 or 20 ft, something a little less than the height of the Seawall. In terms of flood risk reduction for the region, there is little value in setting the height of the 2-mile long Bolivar Roads Barrier to be higher than the 43-mile-long land barrier. However, by setting the height at 19 or 20 ft, it would avoid having to raise the Bolivar Roads Barrier it if a decision was made in the future to raise the height of the land barrier to accommodate a higher rate of sea level rise. The 19 or 20 ft Barrier likely meets the 100-yr design standard for still water level and the intermediate sea level rise scenario, but not the overtopping standard. However, in light of the fact that there is water behind the gates and considering the large water retention capacity of Galveston Bay, it seems unnecessary to meet the overtopping design standard.

In addition, we recommend investigating the benefits, consequences, and potential cost savings that are associated with reducing the crest elevation of the floating sector gates of the Bolivar Roads Storm Surge Barrier. Because of the short duration of very high surge levels during hurricanes and the large water retention capacity of Galveston Bay, JSU research suggests that overtopping/overflow of lower Bolivar Roads gates does not appear to cause large increases in water levels inside the Bay. Reducing navigation gate elevations, and perhaps other gate elevations, will reduce the likelihood and magnitude of negative heads which is a design concern for the sector gates, reduce the magnitude of wave loadings, might improve gate operability, enable some water to exit the Bay under negative head conditions, and reduce costs of the gates. More information about this JSU analysis can be found in Chapter 13 of the JSU (2018) report.

Cost Effectiveness of Implementing the Ike Dike Concept

Davlasheridze et al (2019) showed that the Ike Dike concept is cost effective. Appendix B presents a simple analysis of the cost effectiveness of strengthening the USACE coastal spine, replacing the dual sand dune system with a higher fortified dune, and adding a western section including a gate at San Luis Pass. The analysis utilizes cost and residual damage data provided in USACE (2020). The simple analysis suggests that full implementation of a 17-ft Ike Dike concept, having a fortified dune and a western section of the coastal spine, is cost effective and will improve the benefit-cost ratio for the project.

The cost estimate for the Bolivar Roads Surge Barrier, $13.8B, seems very high, $7B to $10B higher than international experience suggests. This subject is discussed in more detail in Chapter 7, along with a discussion of other aspects of the Surge Barrier. We are concerned that the overly high cost estimate adversely skews the overall project cost, and led to limited consideration of other means for reducing residual damage throughout the region. In light of the overestimate of Surge Barrier cost and information provided in Appendix B, we believe that the cost of improvements to the USACE coastal spine that are needed to fully implement the Ike Dike concept will not change the current total project cost.

Environmental Benefits of the Ike Dike

A western section of the coastal spine provides considerable reduction in storm surge and wave energy that can damage the wetlands that lie behind Follets Island as well as wetlands located elsewhere around the periphery of West Bay, much more so than the USACE Plan provides. The USACE Plan includes an environmental restoration dune on Follets Island (ecosystem restoration measure B-2). Compared to measure B-2, a western section of the Ike Dike provides the same ecosystem restoration benefits as B-2 and far superior protection to the wetlands behind it; and it provides long-term protection not short-term protection like measure B-2. The western section precludes the need for the

B-2 measure and avoids its cost.   A western section also provides damage reduction benefits to ecosystem restoration measure G-28, much more than does the USACE Plan.

Implementing the full Ike Dike concept, including the western section, helps preserve the integrity of the entire G-28 ecosystem restoration measure, which includes elements in both West and Galveston Bays. Ike Dike implementation helps preserve its function and capital investment. These environmental benefits associated with Ike Dike have not been considered and thoroughly analyzed. We recommend doing this particular analysis, along with a comparison to the same types of benefits provided by the USACE Plan, as part of a rigorous and thorough analysis of the benefits and costs associated with implementation of the full Ike Dike concept.

Consideration of Future Sea Level

The USACE process is difficult for large projects involving multiple lines of defense, especially those that expect a long lifetime under changing threats, such as sea level rise (SLR). Accounting for significant future SLR causes larger, more expensive protection schemes than those needed now. And, today's work is obviously constrained to present technologies. Much of this added protection probably won't be needed until much later in the project life. However, not accounting for future SLR in present plans causes the protection to be too weak in the future and availability of future funding for project improvements is uncertain. The process seems to preclude the use of adaptive solutions and adaptive management, which can take advantage of new technologies and evolve in response to changing environmental threats.

Future sea level appears to be treated inconsistently in the design of different elements of the USACE Plan. It appears to have been considered in all gate designs. However, it is not adequately addressed in design of the Galveston Ring Barrier and Seawall improvements, or in design of the dual sand dunes. Consistency in approach and/or clarification of reasons for the inconsistency is needed.

Communication of Residual Surge Levels, Flood Risk, and Damage

We believe it is extremely important to communicate visually and quantitatively to stakeholders what their level of residual risk is with the USACE Plan, in terms of water levels, inundation and residual damage.   Clear communication is necessary because the USACE Plan results in very high residual damages, and because inconsistent design standards are applied to different project elements. We recommend a dedicated section in the feasibility report that describes in great detail, and with highly informative and effective graphics, how the entire Houston-Galveston region responds to a "direct-hit" hurricane that most closely produces the 1% AEP (90% CL) still water level at Galveston (Gulf side). Illustrate with maps of the residual water level, inundation and residual damage. Graphics should be of sufficient quality and scale to enable making reasonably accurate quantitative estimates using them. We also recommend detailed views of Plan performance in the following key sub-regions: western Galveston Island, north shore of West Bay, City of Galveston, Bolivar Peninsula, west side of Galveston Bay, and areas along the Upper Houston Ship Channel. We also believe it is important to show the water levels, inundation and residual damages for a hurricane that exceeds the design-level event, such as a hurricane that produces a peak water level that is closest to the 0.2% AEP water level. It would be informative to show results for the different sea level rise scenarios that are considered. Figure 1-7 in the USACE (2020) main report, which illustrates system response for without project conditions, might be a good starting point for the type of graphic to use for this purpose. The Coastal Texas Study web site provides some nice features, such as the surge maps that can be swiped, a capability that can be utilized as well.

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Chapter 3. Land Barrier Must Be Stronger

Current USACE Land Barrier Concept

The current land barrier concept features a double-dune design and added beach along the open coast of Bolivar Peninsula and West Galveston Island as a combined Coastal Storm Risk Management (CSRM) and Ecosystem Restoration (ER) feature (G5 in USACE report). The proposed Bolivar Peninsula and Galveston Island Gulf beach and dune creation and restoration stretches 25.1 and 18.4 miles, respectively, along the existing beach (total length: 43.5 miles). The beach and dune system would extend from High Island to the Bolivar Roads East Jetty on the Bolivar Peninsula and west of the seawall on Galveston Island all the way to San Luis Pass. The design features a natural double-dune system with a 14-ft landward and a 12-ft seaward dune crest elevation. All elevations are based on NAVD88. Both dunes have a crest width of 15 ft. The base width of the landward dune is 94 ft (somewhat variable based on location) and the base width of the seaward dune is 82 ft. There is an 8-ft gap between the landward toe of the seaward dune and the seaward toe of the landward dune. The landward dune toe is located at 6 ft elevation and the seaward dune toe is located at 4 ft elevation. A nourished beach template is added in front of the seaward dune with a slope of 100H:1V and a beach width of 200 to 250 feet. Figure 3-1 provides a side-view of the proposed dune system template.

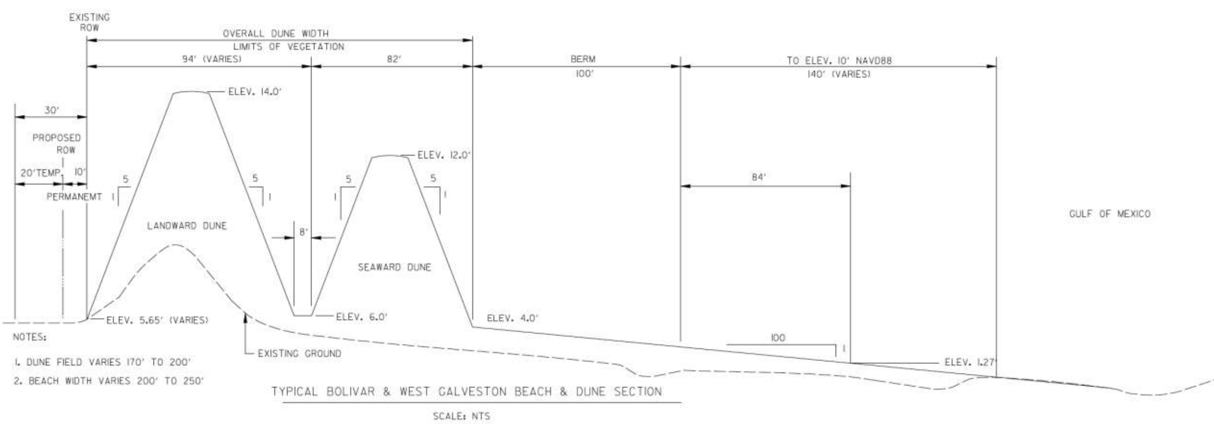

Figure 3-1. Schematic cross-section of the USACE proposed double-dune system profile template (USACE, 2020)

Dunes would be planted with Texas dune grass species (commercially bought or transplanted from natural stands along the coast). Plant grass species include bitter panicum (Panicum amarum), sea oats (Uniola paniculate), and marshhay cordgrass (Spartina patens). Dune fences would be installed at appropriate locations (4 ft above local sand surface as the standard, 2 ft where conditions are poor for dune building).

The USACE report proposes the creation of "43 miles of beach and dune segments on Bolivar Peninsula and West Galveston Island that work with the Bolivar Roads Gate System to form a continuous line of defense against Gulf of Mexico surge, preventing or reducing storm surge volumes that would enter the Bay system" (USACE, 2020, p. 54). Sand volumes needed to create and re-nourish the beach and dune system are provided in Table 3-1. The USACE assumes (based on numerical modeling) that the seaward dune provides a source of material to re-nourish the beach over time.

“The beach feature does not provide a comparable scale of risk reduction as the levee [previous suggestion using set-back elevated roadway], but is placed gulfward of all structures, creates fewer community impacts, and benefits from the natural resiliency of sand systems. The larger beach feature also sustains the barrier features and supports the function of the Bolivar Roads Gate System.” (USACE, 2020, p. 51)

Table 3-1. Sand volumes needed for beach and dune construction and maintenance

Sand Use	Sand Volume	Sand Volume per Unit Length
Bolivar initial beach & dune construction	22.14 million cu.yd	167.12 cu.yd/ft
Galveston initial beach & dune construction	17.19 million cu.yd	177.43 cu.yd/ft
Renourishment (every 6 years on Bolivar and every 7 years on Galveston Island)	21.56 million cu.yd	2.156 cu.yd/ft per year for Bolivar example

Drainage of rainwater based on 100-year design storm were incorporated into the analysis as some developments on West Galveston Island and Bolivar Peninsula drain toward the Gulf of Mexico. A total of 39 drainage culverts (24-in diameter) are proposed for West Galveston Island with flap gates to prevent flow from the Gulf through the dunes. Ditches along the backside of the landward dune are proposed to collect and transport rain storm runoff water and transport it laterally before conveying it to the open ocean. For Bolivar Peninsula a total of 48 drainage culverts (varying sizes) with flap gates are proposed.

It is noted that an additional ER measure consisting of a smaller dune and beach nourishment is added on Follets Island (ER measure B2). The Follets Island Gulf beach and dune restoration stretches over 10.1 miles. A dune crest elevation of 9 ft (NAVD88) and crest width of 12 ft are intended (although USACE, 2020, Appendix D, Section 7.3 states 10 ft of crest width) with 5H:1V slopes. An additional subaerial beach width of 200 ft after profile equilibration is planned via nourishment. Beach and dune construction at Follets Island would require 802,000 cubic yards (cu.yd) of sand. This volume is estimated to compensate for erosion that usually occurs over a 10-year period. Re-nourishment plans are not included due to potential cost-sharing issues.

USACE Methods to Evaluate Dune Design

The dune system design and optimization approach are presented in USACE (2020, Appendix D). The USACE states that crest elevations are based on a damage overtopping limit state with annual exceedance probability of 1%. The assumption is made that maximum water level elevation and wave height occur simultaneously. ADCIRC runs with a fixed dune crest at 12 feet (NAVD88) were conducted to calculate flooding extent for different alternative solutions and different storms. The 12-ft dune height was chosen to acknowledge the effect of dune wave overtopping and overwash before surge levels exceed the dune crest.

Optimization trial simulations using the process-based model SBEACH (Larson et al., 1990) combined with a semi-qualitative approach were used to assess profile performance relative to volume requirements. A range of parameters related to beach and dune geometry were tested including single and double-dune configurations, varying dune side slopes, crest elevations, crest widths, berm slopes, berm top elevations, and berm widths. This analysis showed that maximum profile elevation is key to reduction of overtopping and ensuing dune failure during severe storm surge events and berm width is key to reducing the impact of runup and dune toe scour.

A cross-sectional schematic of the preferred beach and dune configuration is shown in Figure 3-2. The initial profile used for SBEACH simulations of morphodynamics during storm impacts is shown in green.

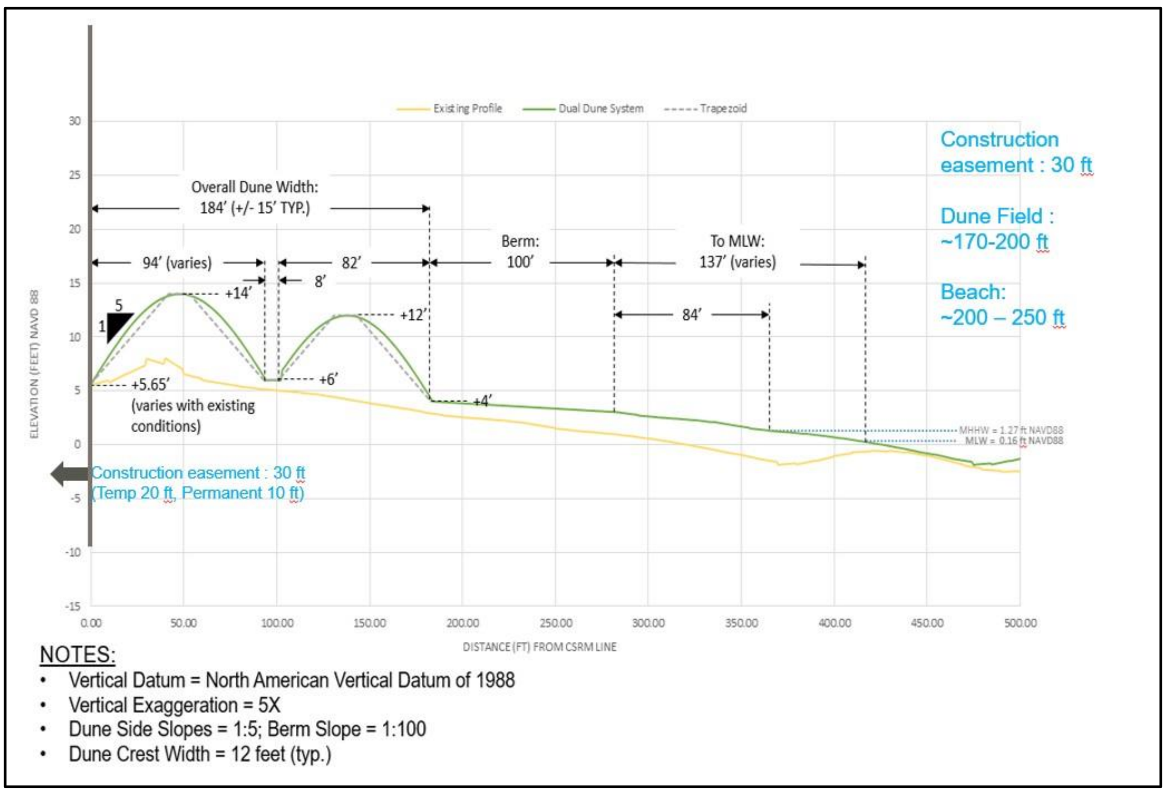

Figure 3-2. Cross-section schematic of preferred dual-dune configuration for the land barrier segments. The green profile shows the input bed elevations for numerical modeling of storm impacts (USACE, 2020).

The USACE report states that historical storms selected for SBEACH simulation had storm surge annual return intervals of 5 (Allison), 10 (Rita), 20 (Frances), and 50 (Ike) years, respectively. Input water levels to the model do not account for relative sea level change (RSLC). Existing beach and dune cross-shore transects out to the depth of closure (estimated at 15 ft water depth) are based on a USACE 2016 Lidar survey for Galveston Island and Follets Island and a 2006 TAMUG survey for Bolivar Peninsula. An example for Galveston transect XS1 is shown in Figure 3-3 where the existing profile and two design profiles for different median sediment sizes of the nourished material are displayed. Here, the existing profile native median sediment size is assumed to be 0.08 mm based on equilibrium beach concepts.

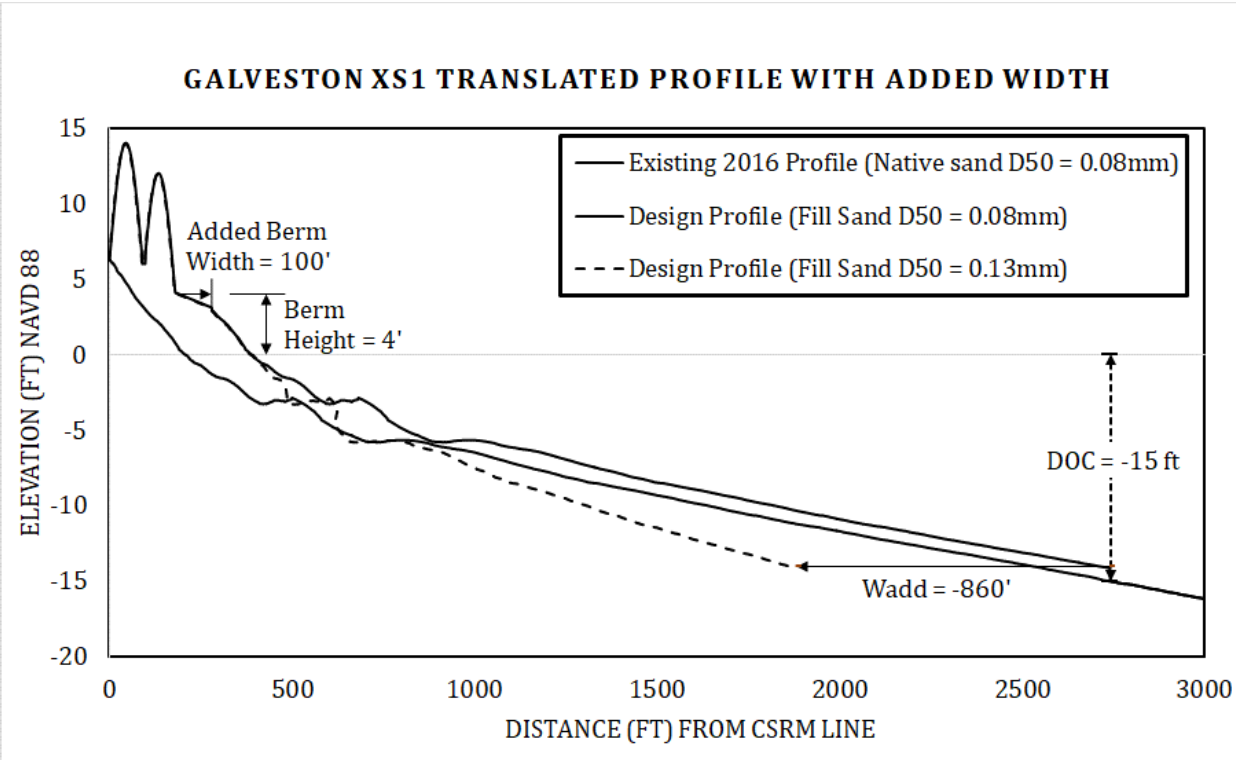

Figure 3-3. Beach profiles out to depth of closure for Galveston representative transect XS1. The measured existing profile (2016) is shown together with two design profiles featuring different median sediment sizes of the fill material (USACE, 2020).

The dual-dune concept requires 16% more sediment volume than a single dune with the same primary dune configuration, although this number seems to assume that the seaward dune is simply added on top of the berm of the single dune design without extending the berm width by the 82-ft base length of the seaward dune. Even with the reduced berm width of the dual-dune design the perceived benefits to erosion resistance during frequently occurring storms seem to outweigh the extra cost based on SBEACH simulation results. The USACE report states that on average the dual-dune system reduces wave height, water depth, and duration of inundation at the CSRM line just landward of the dune system by 87% (from 4.73 to 0.63 ft), 88% (from 9.66 to 1.13 feet), and 95% (from 51.75 to 2.44 hours), respectively, compared to the existing profile based on Hurricane Ike forcing. Furthermore, it is acknowledged that additional analysis is needed to quantify the relative risk reduction.

Sediment for all initial construction of dunes and beaches and maintenance nourishment is tentatively sourced from Sabine and Heald Bank offshore locations (40 mile distance, 40-50 ft water depth) and will be dredged and transported by a large-sized hopper dredge working in concert with track dozers and excavators on the beach to distribute pumped sediment. Sediment input parameters to the SBEACH model are 0.16 mm, 0.14 mm, and 0.13 mm for Bolivar Peninsula, Follets Island, and Galveston Island, respectively.

The USACE report states that during Hurricane Ike simulations "the dune fails quickly once overtopping begins, leaving the upland area exposed to storm surge and direct wave impact". The SBEACH modeling results showing initial and final profiles as well as erosion and accretion areas are shown in Figure 3-4. It is worth mentioning that the USACE SBEACH simulations for Hurricane Ike produce a peak water level (surge + setup) at the coast of 12.84 ft (more than 1 ft below the initial elevation of the landward dune crest). Under these conditions both dunes are completely wiped out.

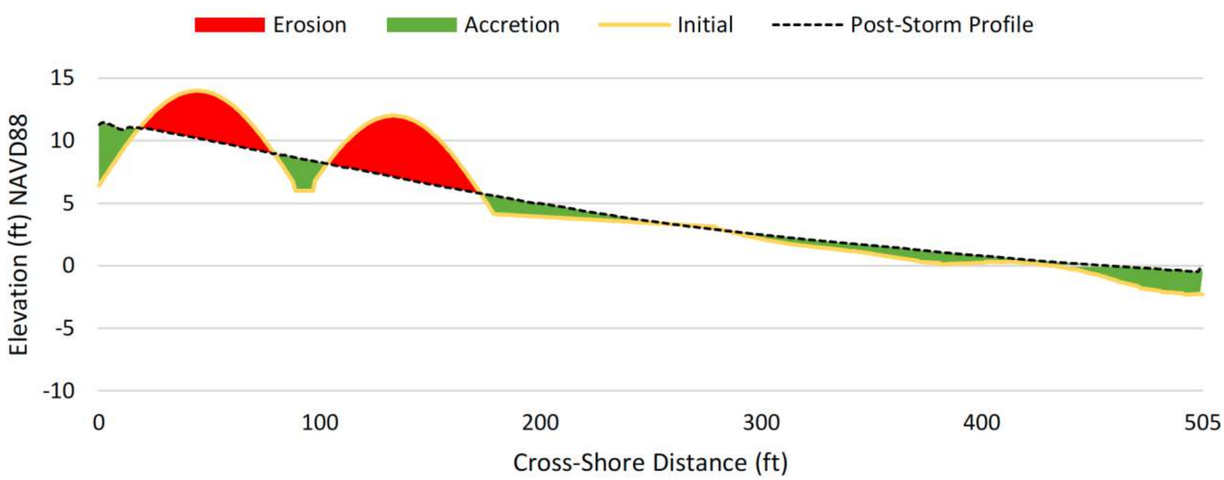

Figure 3-4. Example of storm-induced double-dune profile response to Hurricane Ike forcing for Galveston Island profile XS1 (USACE, 2020)

Core-enhanced dunes were also tested with SBEACH by simulating an impermeable non-erodible core. Simulation results were deemed unreliable and were not considered further in the USACE design efforts. A comment was made, however, that further exploration of this alternative may be worthwhile during the Project Engineering and Design (PED) phase, albeit unspecified concerns regarding potential aesthetic and environmental impacts. Potential wave scour at the toe of such a hybrid structure once exposed was mentioned as an issue along with potential core failure that could spread in the alongshore direction. Another issue raised was the potential for the use of sand over top a hardened core to cause reduced internal stability and promote seepage due to different material properties. These concerns are not substantiated with further calculations.

Positive Aspects of USACE Land Barrier Design

The USACE is to be commended for selecting a land barrier along the open beach instead of levee solutions further back. The idea of a beach nourishment effort to support the dune component of the land barrier and bolster regional sediment supply is also a great feature of the current plan where the added beach width helps reduce wave energy that reaches the dune line during surge events. The choice of a dual-dune system instead of a single dune certainly adds a needed level of resiliency against storm impact and erosion and is viewed as a positive aspect of the plan, providing additional buffer capacity.

The USACE report does state that dune and beach systems are soft coastal features and that prevention or mitigation of inundation with the proposed design profiles is not solely predicated on dune failure itself, but on when and how the dune fails. Additionally, USACE states that the “buffer” provided by the seaward dune affords some extra time before failure during storm impact which is crucial for risk mitigation.

The choice of 1V:5H slopes for the dunes is a good choice to mimic the slopes of existing “healthy” dunes on Galveston Island and to aid vegetation advancement. Selecting native Texas dune vegetation species for planting efforts is also a great feature of the proposed plan.

The USACE is to be commended for their special consideration of drainage from rainwater runoff toward the Gulf through the dunes via culverts and flap gates. If runoff drainage is not treated properly, dune and beach scouring, culvert damage, clogging, and hazardous beach conditions can ensue. The USACE states that conveyance of runoff to bayside outfalls instead of Gulf-side outfalls would alleviate many of the concerns related to runoff flows being conveyed alongside and through the dune system. This is an important aspect of the overall functionality of the storm risk reduction system and should not be neglected during the PED phase.

The inclusion of proper walkovers and vehicle ramps that do not compromise the integrity of the dune system is viewed favorably, as well as the inclusion of sand fencing and drainage structures.

The proposed plan to start construction of the whole system with the dune and beach is a good idea, as long as the construction of the Bolivar Roads Gate System commences in parallel. The gates reduce inflow of water into the bay even without the land barrier in place as soon as they are functional and can be closed at the appropriate time. The proposed idea to start land barrier construction with the Bolivar Peninsula dunes and beaches adjacent to the Bolivar Roads north jetty working outward is good and should be mirrored on Galveston Island starting at the west end of the seawall working outward toward San Luis Pass.

Shortcomings of USACE Land Barrier Design

The desire to balance residual flood risk due to overtopping and breaching of natural dunes during storm impact with some stakeholder recommendations to mimic existing/natural conditions as much as possible creates a dangerous situation during those situations for which the entire system has been conceived in the first place: overall risk reduction during storm impact. The creation of such a weak link compromises the entire system during time of need. It also has to be recognized that Galveston dune systems have been degraded over a long time and basing a storm surge barrier design on a degraded system is not sufficient.

The notion that a fixed 12-foot dune elevation during ADCIRC storm impact simulations is a proper representation of the degraded dune and/or wave overtopping before surge levels reach the actual 14-foot crest is a dangerous assumption that ignores the actual dune morphodynamics during storm impact. A 12-foot high solid wall is much more efficient at reducing flooding from storm surge and wave overtopping than a dune breached completely at multiple locations. The USACE life-cycle modeling using CSHORE coupled with Monte-Carlo simulations of storm forcing showed that the dual-dune system experiences maximum crest elevations below 12 ft (2-ft crest elevation reduction) over significant portions of its 50-year life-cycle between renourishments. For the Galveston dual-dune profile XS1 this is the case for over 70% of the time for both the high and low RSLC estimates, respectively. Furthermore, process-based cross-shore only (1-D) models such as SBEACH (used by the Galveston District for dune design) and CSHORE (used by ERDC for life-cycle modeling) tend to understate dune breach channel formation and ultimately the risk of flooding. A more realistic assumption for a fixed elevation of this dune system to be used for ADCIRC computations should be closer to 9 ft considering the life-cycle analysis and breaching underrepresentation. It is also not clear how the USACE design dune crest elevations are based on a damage overtopping limit state with annual exceedance probability of 1% as stated in their report.

SBEACH runs utilize offshore NOAA buoy data on waves to drive model simulations. It is not described in detail how the transformation of these waves as they approach the shoreline (refraction, shoaling, diffraction) is handled (i.e. what bathymetric assumptions were made) and whether nonlinear effects and effects related to infragravity waves were considered. These processes can increase runup and erosion levels at the shore- and dune-line significantly, especially in such a shallow-slope environment as the Texas coast.

The current dune morphodynamic simulations under storm impact using SBEACH do not include RSLC scenarios. PED phase recommendations include life-cycle analysis probabilistic modeling accounting for background erosion and RSLC. A comment is made in the USACE report that this may require updates to the dune design to accommodate new findings. It seems strange that a wide range of dune geometric parameters were tested with the SBEACH model, but potential water level increases were not accounted for. This would be an easy addition to the modeling, especially since the relative elevation of the dune crest to peak surge levels is one of the most critical components in the evolution (or destruction) of a dune during storm impact. Another aspect that is not yet considered is the effect of gradients in alongshore sediment transport and how they may affect renourishment volumes and frequencies.

The proposed natural dual-dune system with 14 ft and 12 ft crest heights, respectively, is only shown to be able to withstand (with significant erosion of the seaward dune) storm impact produced by TS Francis at present sea level conditions based on SBEACH results (Figure 3-5). The USACE report lists TS Francis as having a 20-year annual return interval (ARI) but in fact surge levels for TS Francis are closer to the 5-year ARI based on NOAA water level data from the Pleasure Pier gauge on the Gulf side of Galveston Island. Based on the same gauge data, the maximum recorded water levels for storms Allison, Rita, Frances and Ike were 3.9, 4.0, 5.5, and 11 ft (NAVD88), respectively. Based on Figure 2-22 (USACE, 2020, Appendix D, p. 2-31) which shows hazard curves at 90% confidence interval without relative sea level change, these four storms are 2-, 3-, 5-, and 30-year water level events, respectively. In addition, the ERDC CSHORE modeling suggests complete dune destruction during Hurricane Ike with its 11-ft maximum water level corresponding only to a 30-year return value. This simply seems too weak of a protection level, especially in light of the fact that such a weakness in the overall system will compromise the intent to keep surge waters out of Galveston Bay and thus render all other features less effective (Bolivar Roads Gates) or under-designed (in-bay measures).

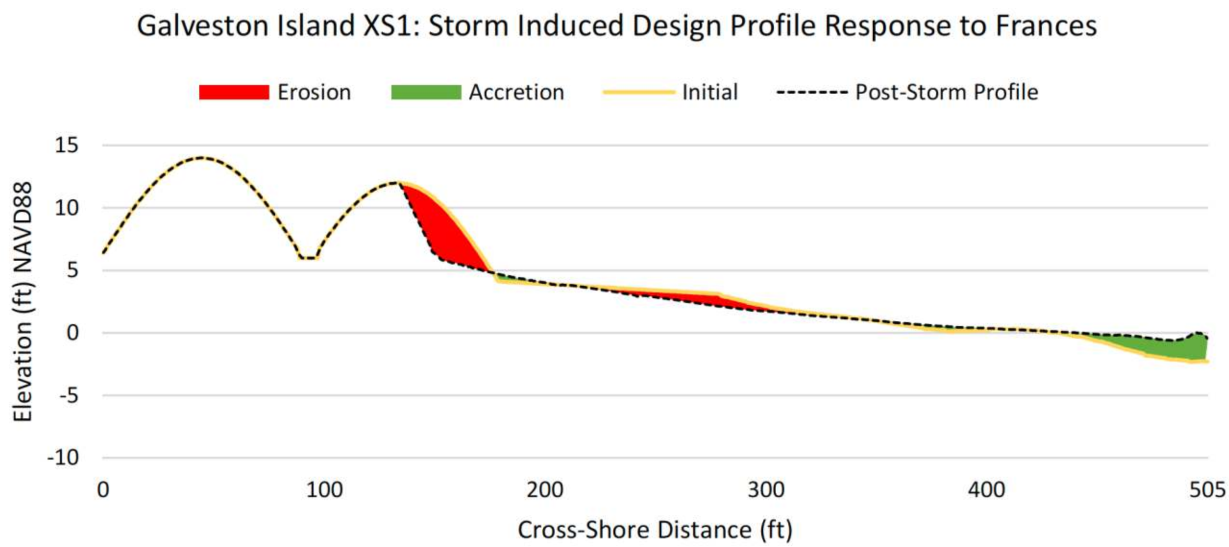

Figure 3-5. Example of storm-induced double-dune profile response to TS Francis forcing for Galveston Island profile XS1 (USACE, 2020)

Potential Alternative using Core-Enhanced Dunes / Hybrid Coastal Structures

A natural dune capable of safely defending against the 100-year design storm conditions was determined to be 22 feet high, 300 feet wide, and have a 150-foot wide crest through work conducted by a TU Delft M.Sc. student (Rodriguez Galvez, 2019) using the numerical model XBeach (Roelvink et al., 2009) to verify the performance of the dune under design conditions The crest width proposed by Rodriguez Galvez (2019) is 10 times the width of one of the USACE proposed dunes in the current plan. The required footprint is thus significantly larger than the one currently envisioned by the USACE and existing viewshed concerns would be exacerbated by this crest elevation (8 feet higher than USACE proposed maximum dune crest elevation). Alternatives that limit footprint and elevation while at the same time preserve the natural fabric and aesthetics of the coastal system are needed.

One viable alternative for the land barrier that can alleviate the issue of a compromised dune system during severe storm impact while preserving the aesthetics and ecosystem functions of a natural dune is a core-enhanced dune, sometimes referred to as a hybrid coastal structure (Almarshed et al., 2020). This option is mentioned in the USACE document but not further pursued due to numerical model limitations and other arguments that are not further elaborated or substantiated in the USACE report. Some of the arguments mentioned against core-enhanced dunes are related to aesthetic and environmental concerns, toe scour, and internal stability due to seepage flows between different materials. None of these arguments seem warranted. Core-enhanced dunes look exactly like natural dunes from the outside and provide the same ecosystem functions. Toe scour can happen but is deemed a small issue compared to the devastating destruction of a natural dune during storm impact. Furthermore, the sand cover helps alleviate toe scour issues: during intense storms with overtopping and overwash, the average sediment transport direction is landward and no substantial toe scour forms. During less intense storms, the sediment cover helps reduce the potential for toe scour formation. Internal stability issues due to seepage flows at the interface between different materials making up the hybrid structure are also not as critical as a destroyed natural dune and can be avoided through proper design (i.e. filter layers, etc.).

Core-enhanced dunes consist of a hard core covered by a layer of sand. They combine effective surge suppression characteristics of the core structure with the aesthetic appeal and ecological benefits of dunes. These hybrid systems look and feel like natural dunes but their performance during storm impact is much improved. Figure 3-6 shows a schematic of hybrid coastal structure dynamics during storm impact to provide an idea how the concept works. A key point is that the fortified dune provides resilience when it is overwashed. The structural core will remain standing and limit inflow and flooding. A regular dune would be eroded and breached and this would also lead to more flooding.

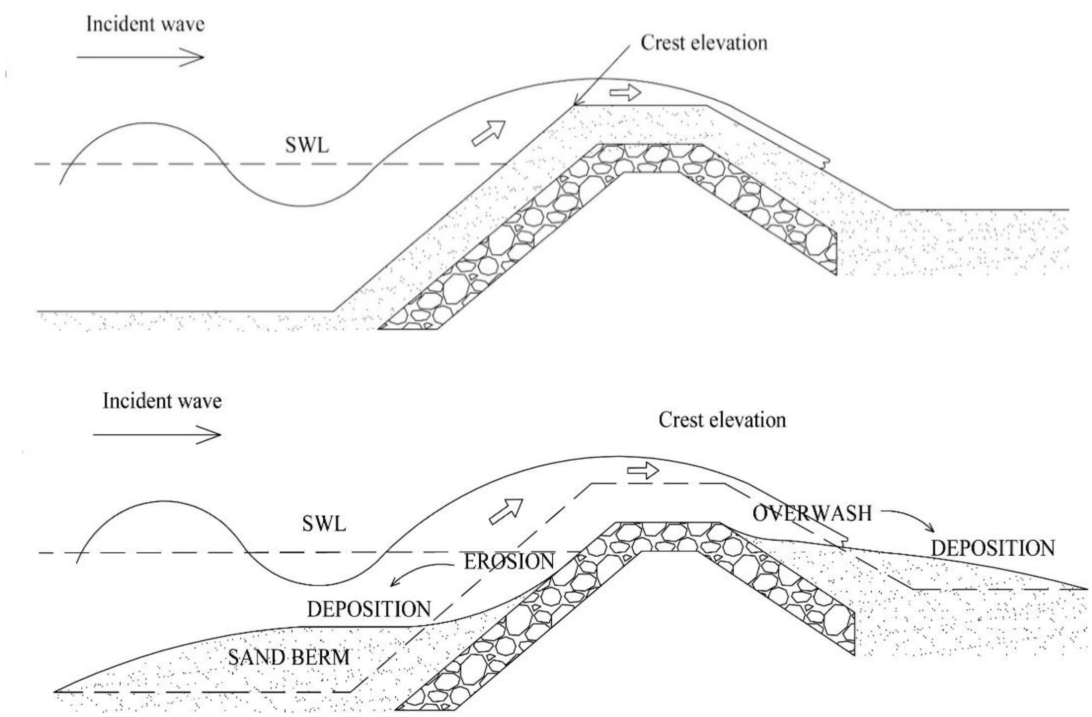

Figure 3-6. Schematic of hybrid coastal structure dynamics under severe storm impact including wave overtopping and sediment overwash. The shown example utilizes a rubble mound as the solid core.

Core alternatives include structures made from clay, reinforced concrete T-wall elements, rubble mound material, or combinations thereof. The sand cover thickness can be varied as needed. In the following, beneficial characteristics of core-enhanced dunes are listed:

- Core-enhanced dunes look and feel like natural dunes.
- They can be vegetated just like natural dunes.
- Dual-dune design proposed by USACE can be adapted using a core-enhanced version for the landward dune. This can help alleviate the restraints on dune elevation due to viewshed concerns that would arise with a natural dune system sized to withstand design storm conditions.

- Core structure can guarantee fixed level of protection without the risk of complete breaching and unobstructed landward-directed flood flow as is possible with all natural dunes.
- At the same time, the sand cover still affords some of the beneficial flood risk reduction aspects of natural dunes during storm impact (i.e., erosion buffer, self-healing effect through re-deposition of eroded dune material)
- Variable core designs are conceivable (clay, T-wall, rubble-mound, or combination thereof) and can be chosen based on desired characteristics, costs, and availability of material.
- Sand cover thickness is variable and can be adjusted to accommodate RSLC or updated design conditions in the future.
- Environmental functionality of hybrid dunes remains intact (sea turtle nesting, vegetation growth, bird nesting).
- Walkover and vehicle access structures can be used as currently anticipated by the USACE.
- Proposed rainwater runoff drainage structures (culverts with flap gates) can be integrated into hard core structure in such a way that the creation of weak points in the surge defense system can be avoided. Running culverts through natural dunes can create preferential scour paths and can easily induce culvert breakage.
- The sand volume required to build and maintain the core-enhanced dunes is less than that for natural dunes.
- The self-healing function of the beach-dune system during storms where sand material from the frontal face of the dune is eroded under wave impact, transported offshore, and deposited as a submerged bar to reduce wave energy at the dune is still functioning with a hybrid system.
- During severe storm impact the volume of sand overwashed over the crest of the hybrid structure and transported into the landward residential areas is much reduced from a natural dune. This reduces the hazard of sand deposits that can cover roadways, drainage infrastructure, evacuation routes, emergency access roads, etc. Thus, the hybrid design allows for quicker recovery after storm impact and improved community resilience against flood damage.
- While toe scour at the seaward edge of the core structure during storm impact is a possibility, the sand cover does provide material to limit the potential of scour formation. During significant overwash, the transport of sediment is primarily landward-directed and toe scour is not an issue. For less severe storms, the sand cover eroded from the hybrid dune face alleviates the scour issue. Additional toe scour protection can be added if necessary. If a dual-dune hybrid system is adapted, the seaward dune affords additional scour protection and we do not foresee significant scour issues.
- The core-enhanced dune system provides consistent surge protection while being far less dependent on renourishment cycles compared to an all-natural dune system. This increased resiliency is particularly important in situations where back-to-back hurricanes occur in the same season or multiple hurricanes occur over several seasons without renourishment of the dune and beach taking place. Thus the core-enhanced dune system will be much more amenable to a periodic renourishment plan than an all-natural dune system, which could remain in a degraded state awaiting renourishment for a long time.

It has to be noted that the lee side of the core structure will have to be designed in such a way as to withstand scouring from overtopping flow and seepage flow induced by external water level gradients between the ocean and bay side during storm impact with the added benefit that the sand cover will help reduce design requirements to some extent.

Core-enhanced dunes have successfully reduced coastal flood risk and erosion in many locations around the world. Some examples are shown in Figure 3-7.

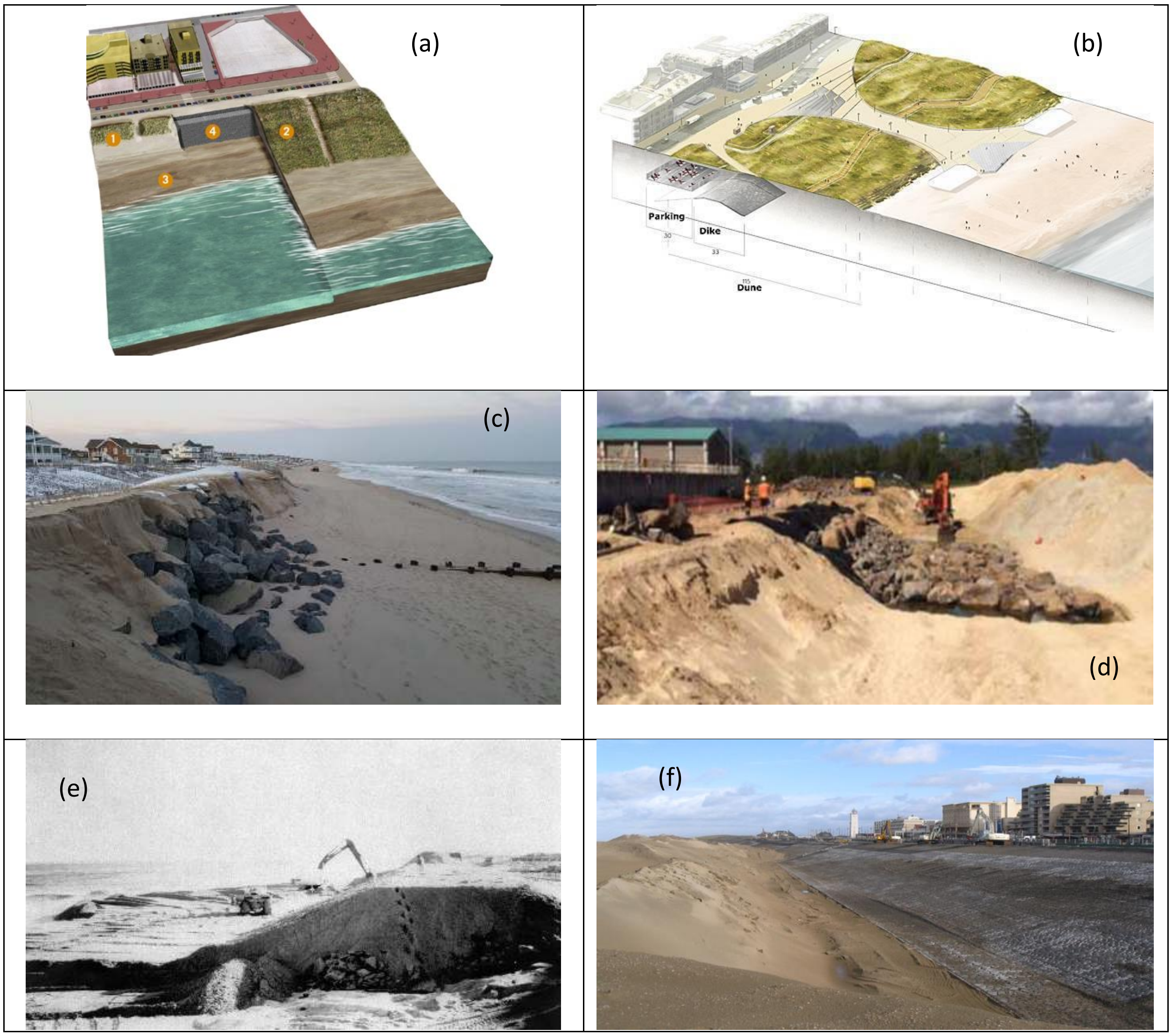

Figure 3-7. Examples of existing core-enhanced dunes from (a) Noordwijk, the Netherlands, (b) Katwijk, the Netherlands, (c) New Jersey, U.S., (d) Hawaii, U.S., (e) Virginia, U.S., (f) Scheveningen, the Netherlands.

Performance of Normal and Core-Enhanced Dunes under Design Storm Conditions

In the following, select results from numerical model runs using the process-based cross-shore morphodynamic model CSHORE (Johnson et al., 2012; Kobayashi 2013) are presented. CSHORE is the same model used by the USACE Engineering Research and Development Center (ERDC) for the morphodynamic component of their life cycle beach and dune evolution analysis of the various land barrier dune configurations (USACE, 2020, Annex 1). CSHORE is a robust process-based cross-shore hydrodynamic and morphodynamic numerical model capable of computing beach and dune profile evolution under varying hydrodynamic forcing conditions.

A variety of storm conditions and dune designs (natural and hybrid) have been evaluated using CSHORE. A brief introduction to CSHORE, the complete set of hydrodynamic forcing conditions, and an extended set of profile evolution results are provided in Appendix A. The few example outputs shown here are intended to provide a feel for the dune system (natural and hybrid) response to storm forcing. Emphasis is on the temporal evolution of the dune system profiles during storm impact since it is critical to quantify the duration over which a dune system can provide adequate protection against flooding.

Figure 3-8 shows time series of hydrodynamic forcing conditions used as input to CSHORE model runs. Water level change (WL), root-mean-square wave height (H_{rms}), peak wave period (T_p), and mean wave direction (θ_m) for proxy storms with defined ARI (10-year, 100-year, 500-year) as well as Hurricane Ike are shown at the location of the ADCIRC output point S11, just offshore of west Galveston Island in 14 m water depth.

Figures 3-9 and 3-10 show some example CSHORE model results of profile evolution under Hurricane Ike storm forcing for natural dunes as well as core-enhanced dunes. Figure 3-9 uses the USACE dual-dune geometry while Figure 3-10 uses a similar geometry but with increased crest elevations. Note that profile evolution is only shown until the onset of significant overwash and dune crest reduction since the CSHORE model is not intended to deal with inundation flows and dune breaching.

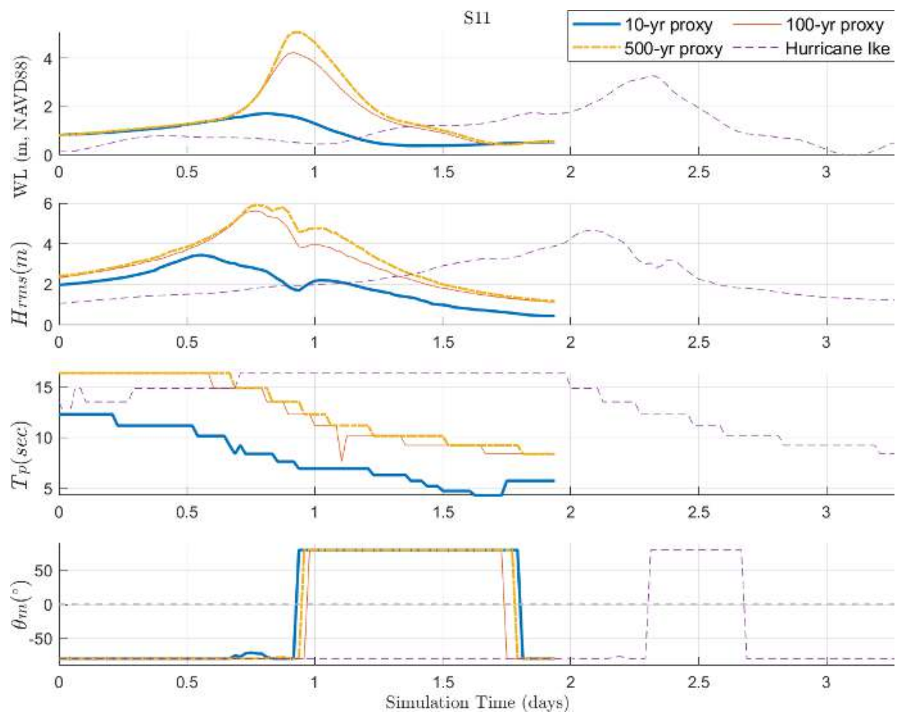

Figure 3-8. Hydrodynamic input parameter time series for various storm forcing conditions (adapted from Ebersole et al., 2018).

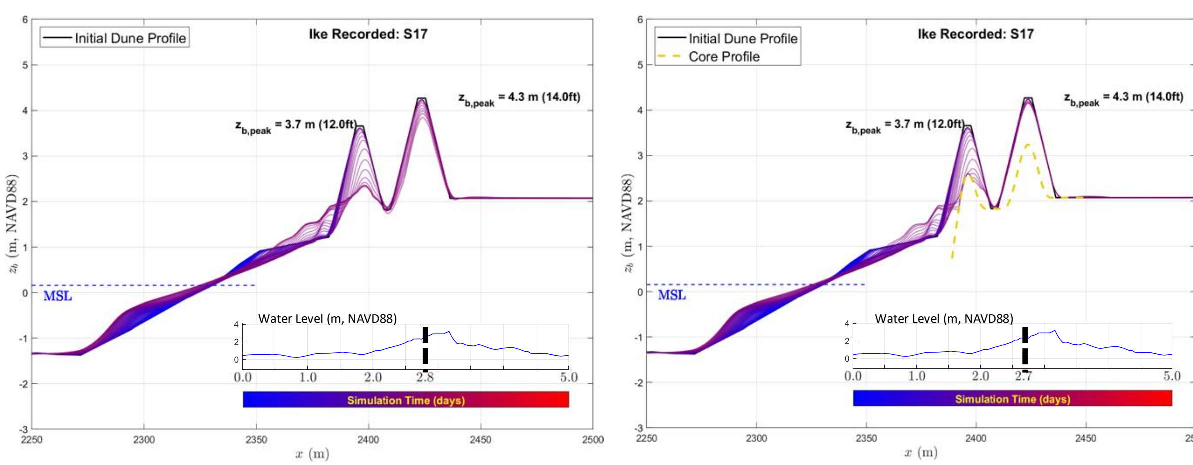

Figure 3-9. CSHORE modeled output of beach and dune profile evolution under Hurricane Ike hydrodynamic forcing (30-year water level event). The initial profile is the USACE dual-dune design (12 and 14 feet crest elevation). The left panel shows the results for an all-natural dune system up to the point of landward dune failure initiated by significant overwash and dune crest reduction which commences well before peak water level is reached. The vertical dashed line in the inset figure shows the time of the last plotted profile. The right panel shows the results for a dual-dune system of the same geometry but with added solid cores. While the core-enhanced dunes still experience overtopping, flood-risk reduction is much enhanced since the core structure cannot be breached.

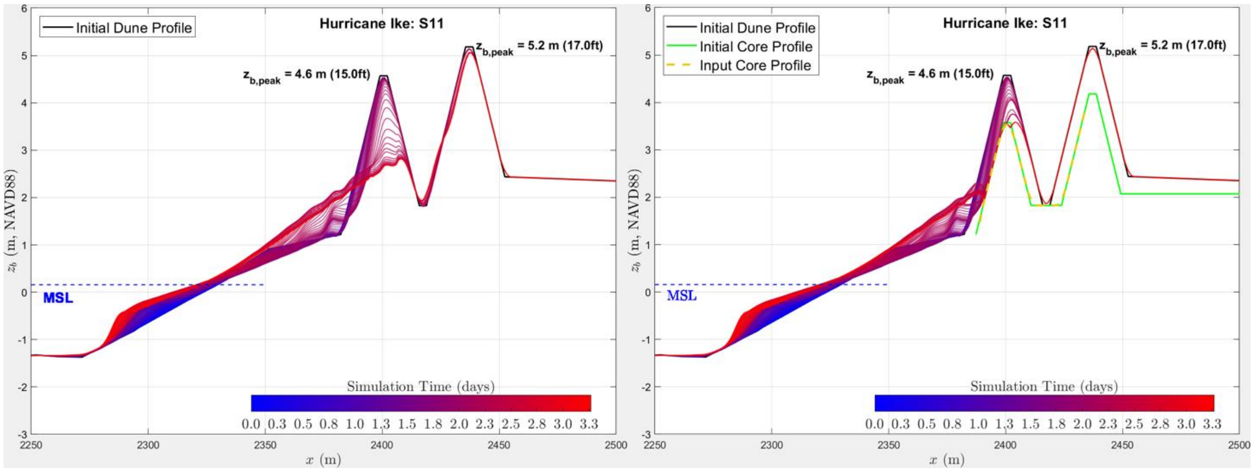

Figure 3-10. CSHORE modeled output of beach and dune profile evolution under Hurricane Ike hydrodynamic forcing. The initial profile is the USACE dual-dune design but with increased dune crest elevations (15 and 17 feet crest elevation). The left panel shows the results for an all-natural dune system. The right panel shows the results for a dual-dune system of the same geometry but with added solid cores. The combination of increased dune crest elevations and solid core strongly enhance flood-risk reduction.

The modeling confirms that the dual-dune system with 12 and 14 foot height does get eroded during a Hurricane Ike type event with landward dune failure commencing several hours before peak water levels are reached (Figure 3-9). Increasing the crest elevations of both the seaward and landward dunes alleviates the situation for an Ike-type storm. The profile evolution results in Figure 3-10 indicate that for a combination of a 15-ft seaward dune and a 17-ft landward dune, only the seaward dune gets completely eroded during an Ike-type storm. If core structures are added (right panel of Figure 3-10) the amount of eroded sediment can be further reduced, limiting the amount needed for renourishment.

The 100-year return storm of course also erodes the USACE dual-dune design with crest elevations of 12 and 14 ft, respectively. In Figure 3-11 a system with an elevated crest height (15 and 17 ft), a 1.5 times wider crest for each dune, and a core structure in the seaward dune is shown as an example of the performance of a modified system under 100-year return storm impact plus elevated sea level of an additional 2.1 ft. The figure shows the profile evolution over the entirety of the design storm. Even though severe erosion takes place on both dunes, overall crest elevation of the system remains above 12 ft. Figure 3-11 is merely an example to highlight that core-enhanced dunes can be designed to provide sufficient flood-risk reduction to maintain the integrity of the entire system during design storm conditions and expected RSLC.

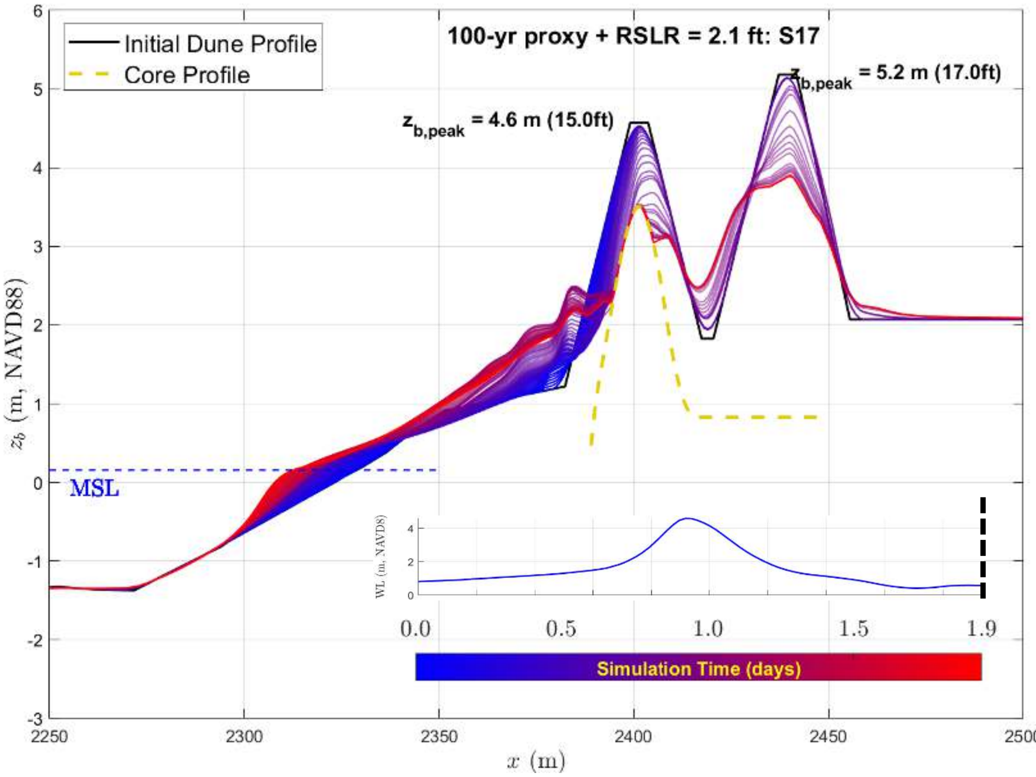

Figure 3-11. Example of CSHORE modeled profile evolution under 100-year storm water level conditions with added sea level rise of 2.1 ft for a dual-dune system with hardened core structure in the seaward dune.

Recommendations

The dual dune system design proposed for the land barrier segment on Galveston Island and Bolivar Peninsula does not provide adequate protection against storm surge and wave impact. The dune system consisting of a 12-foot seaward dune and a 14-foot landward dune does not withstand a 100-year return value event or even Hurricane Ike, a 30-year water level event. SBEACH and CSHORE numerical modeling confirm the complete destruction of both dunes during an event similar to Hurricane Ike.

It is clear that the land barrier needs to be more robust against storm impact to guarantee the integrity of the entire system. We recommend the use of core-enhanced dunes (i.e., hybrid structures) as part of a hybrid dual-dune system, potentially with a seaward natural dune and a landward core-enhanced dune. With this recommendation the following scenario can be avoided:

A hurricane of magnitude similar to Ike or even less, breaches and obliterates the dune system at multiple locations along the Bolivar Peninsula, leading to relatively uninhibited overland flood flow into Galveston Bay right next to the very expensive 21.5-ft high Bolivar Roads Storm Surge Gates. In such a situation, high strong gates are not needed and even though the gates will prevent a significant portion of flood waters from entering Galveston Bay through the Bolivar Roads inlet, the breached dune system will provide the path of least resistance for flood waters to enter the Bay and lead to flood damages that can be avoided with a stronger land barrier.

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Chapter 4. Consequences of Leaving San Luis Pass Open

Introduction

Layouts of the USACE coastal spine and the Ike Dike concept were compared in Chapter 2. It was noted there that the USACE coastal spine is essentially the middle section of the Ike Dike shown in Figure 2-1, without the eastern and western sections. Also, as mentioned in Chapter 2 and discussed much more in Jackson State University, JSU (2018), the storm surge reduction benefits of the middle and western sections far exceed those of the eastern section. In the USACE Plan, omission of the important western section, which includes a gate system at San Luis Pass and a land barrier on Follets Island, is the basis for the concerns expressed here.

The Ike Dike concept achieves its effectiveness by minimizing entry of the open-coast storm surge into West and Galveston Bays, suppressing generation of internal surge. Once storm surge enters the large, very shallow bays, hurricane-force winds are extremely effective in dragging water from one side of the bay to the other, leading to even higher surge levels on the down-wind side. The specific areas around the Bay's periphery impacted by the enhanced surge can change rapidly as a hurricane transits through the region. The middle section of the Ike Dike concept significantly reduces storm surge entry into the Bays; but so does the western section. Omission of the western section is akin to leaving a "back door" open; it significantly compromises the performance and effectiveness of the coastal spine.

As illustrated in later sections, omission of the western section leads to large increases in peak storm surge throughout West Bay and lesser, but still significant, increases in Galveston Bay. It does so through the following two mechanisms: 1) allowing the hurricane surge forerunner to propagate through San Luis Pass into the Bays, in the days leading up to hurricane landfall, and 2) allowing the main storm surge to flank the western end of the coastal barrier, initially via San Luis Pass and then via an inundated Follets Island, as the hurricane approaches and makes landfall. Increases in peak surge lead to greater flood risk and damage to most, if not all, areas of the Houston-Galveston region fronted by the coastal spine. Adverse impacts are substantial for communities and industries in Brazoria and Galveston Counties that ring West Bay, including all of Galveston Island, as indicated by the high residual damage that remains even with the USACE Plan (see Chapters 2 and 6). Impacts can extend into Galveston Bay and far up the Houston Ship Channel, as surge penetration from West Bay into Galveston Bay occurs. As discussed in JSU (2018) and later in this chapter, rising sea level will exacerbate adverse impacts associated with leaving the "back door" open, throughout the entire Houston-Galveston region. Results from storm surge model simulations, upon which conclusions regarding omission of a western section are based, are described in more detail below.

We recommend that the USACE conduct a thorough analysis of the benefits and costs associated with a western section of the coastal spine, which includes a gate at San Luis Pass. Benefits include direct reduction in damage as well as cost avoidances that arise from being able to reduce design water levels and wave conditions for all in-bay second lines of defense and non-structural measures, which in turn reduces the required extent strength, height and cost of all in-bay measures. The stated goal for the USACE Recommended Plan (the Plan), in USACE (2020), is to "promote a resilient and sustainable economy by reducing the risk of storm damage to residential structures, industries, and businesses critical to the Nation's economy." Examples are shown below that illustrate how achievement of the stated goal is compromised by leaving open a "back door" to West and Galveston Bays. We strongly recommend that the USACE re-evaluate the decision to omit a western dike/gate section in the USACE Plan.

Investigative Approach

To examine the impacts of omitting the western section, storm surge simulations were made for two different alignments of a coastal spine. Each alignment had a different combination of the Ike Dike coastal spine sections shown in Figure 2-1. The Ike Dike concept was comprised of all three dike sections (middle + eastern + western). An alignment comprised of two of the sections (middle + eastern), but with no western section, was also evaluated to isolate the effects of omitting the western section. The crest elevation of all dike sections considered in the surge simulations, for both alignments, was 17 ft, NAVD88.

A set of eight hurricanes was simulated for both coastal spine configurations using the USACE Coastal Modeling System (which includes the ADCIRC storm surge model). Simulated hurricanes were selected from among historic and hypothetical, idealized storms that were considered in the FEMA RiskMap study that was most recently performed for the Texas coast. A summary of the characteristics for all eight simulated hurricanes is provided in Table 4-1.

Table 4-1. Characteristics of Simulated Hurricanes

Storm Identifier	Central Pressure (mb)	Maximum Wind Speed (kt)	Forward Speed (kt)	Radius-to-Maximum-Winds (nm)	Target Average Recurrence Interval Water Level, Location
Hurricane Track 1					
Storm 019	960	88	11	11	10-yr, San Luis Pass
Storm 023	930	102	11	18	100-yr, San Luis Pass
Storm 027	900	113	11	22	500-yr, San Luis Pass
Hurricane Track 2					
Storm 3001	930	102	20	18	100-yr, San Luis Pass
Hurricane Track 3					
Storm 535	975	68	6	18	10-yr, Galveston Bay
Storm 033	930	100	11	26	100-yr, Galveston Bay
Storm 036	900	112	11	22	500-yr, Galveston Bay
Hurricane Ike Track					
Ike	950	80	10	45	

Staff at the USACE Engineer Research and Development Center's Coastal & Hydraulics Laboratory made the surge model simulations; Jackson State University staff performed the analysis of model results.

Hurricanes were selected using the following rationale. Hypothetical hurricanes were selected to best replicate peak surge levels associated with different average recurrence intervals at two locations, as indicated in Table 4-1, for the without-project condition. One set of hypothetical storms was selected to replicate 10-yr, 100-yr and 500-yr water levels along the western shoreline of Galveston Bay and into the upper reaches of the Houston Ship Channel. These are the areas with the highest potential for economic damage and losses. A second set was identified that replicates the 10-yr, 100-yr and 500-yr water levels at the entrance to San Luis Pass. Storm surge at the entrance to San Luis Pass strongly influences the amount of water that enters through the open "back door." The most intense hurricanes (having 900 mb minimum central pressure) are those that closely replicate the 500-yr water levels; less intense hurricanes (having a 960 or 975 mb minimum central pressure) are those that closely replicate the 10-yr water levels. Hurricane Ike was selected because of the high surge forerunner and peak surge it created in the Houston-Galveston Region, and its relatively recent occurrence.

Simulated hurricanes followed one of the four tracks shown in Figure 4-1. Historically, severe land falling hurricanes that have influenced the Texas coast have generally approached from the southeast, like Hurricane Tracks 1 and 3 and the track for Hurricane Ike. Occasionally they have approached from the south, like Track 2. Hurricane Harvey approached from the south.

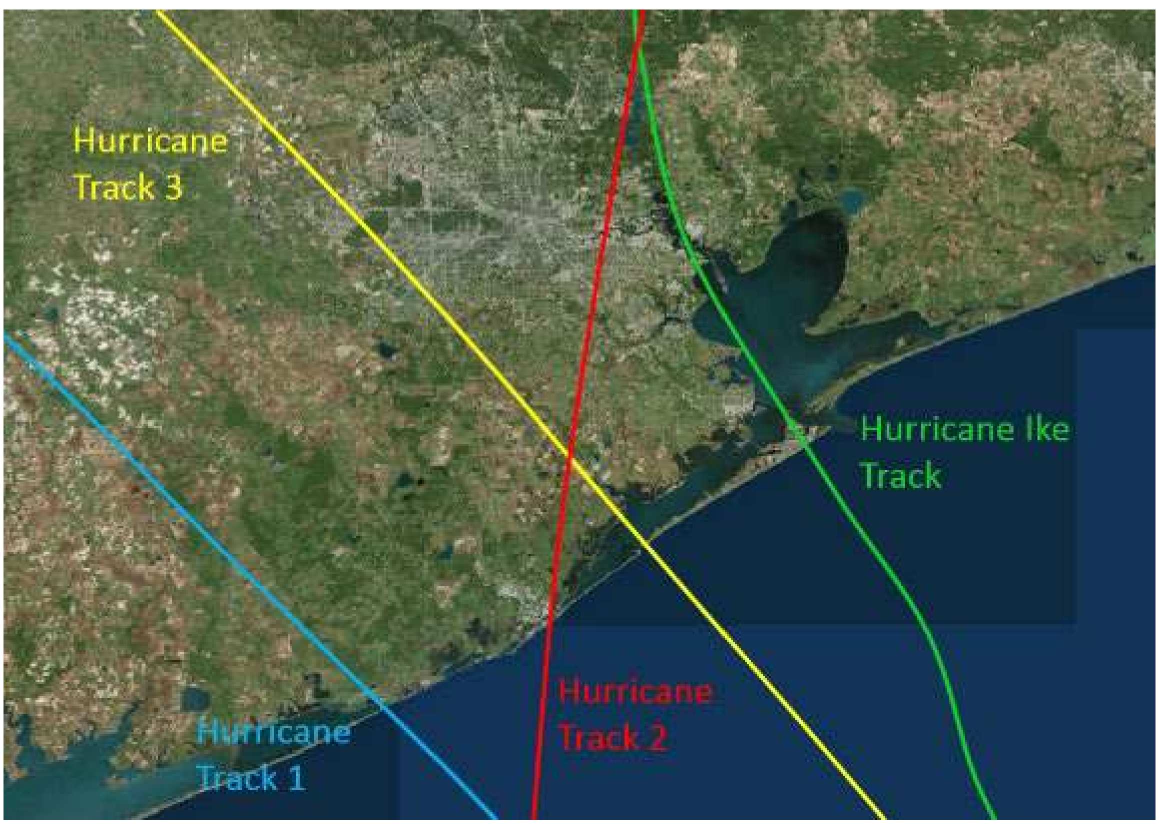

Figure 4-1. Different tracks considered in the hurricane simulations

Simulations were made for each storm identified in Table 4-1, for each of the two coastal spine alignments (with and without a western section), and for both a present mean sea level (0.9 ft NAVD88) and a future sea level scenario that is 2.4 ft above present sea level (3.3 ft NAVD88). This future sea level is the level projected for the year 2085 using the USACE methodology and assuming an intermediate rate of sea level rise. The modeling approach employed reflects the current state of engineering practice, which does not include the effects of hurricane rainfall in the storm surge simulations.

Results are presented for three different aspects of the increased damage and flood risk which results from omission of a western section. The first is surge forerunner propagation through an un-gated San Luis Pass. The second is increase in peak surge elevation and inundation in both West and Galveston Bays caused by the main storm surge that flanks the western end of the USACE coastal spine. The third is the influence of sea level rise on increased peak surge and inundation associated with flanking. All three aspects are discussed in separate sections below. A series of figures visually illustrate the adverse impacts on flood risk and expected damage that arise from omission of the western section, in different parts of the Houston-Galveston region.

Hurricane Surge Forerunner Generation and Propagation through San Luis Pass

Major hurricanes that traverse the Gulf of Mexico, and eventually approach the north Texas coast, can generate a significant surge forerunner. The combination of the quarter-circle shape of the Louisiana/Texas coastline and continental shelf in the northwest corner of the Gulf and the circular wind field about the eye of an approaching hurricane is conducive to formation of a wind-driven forerunner. The forerunner is forced by far-field hurricane winds that circulate in a counterclockwise direction about the hurricane's eye while it is still well offshore in the deep Gulf. Such far field winds blow from east to west to southwest over the Louisiana and north Texas continental shelves. These winds tend to force an east-to-west movement of water along the shelf, which is turned to the "right" in the northern hemisphere by the Coriolis force, and stacked against the Louisiana and north Texas coastlines. The Coriolis force is associated with the earth's rotation. This stacking of water against the shoreline is called Ekman set-up. This is the physical process behind formation of the wind-driven surge forerunner. The forerunner begins as a forced wave that advances along the northern Gulf shelf from east to west with the advancing storm; but then, after landfall on the north Texas coast, the forerunner propagates as a free wave southward along the south Texas continental shelf. This along-shelf propagation of the surge forerunner was first shown for Hurricane Ike by Kennedy et al (2011).

The forerunner is experienced at the coast as a slow steady rise in the water surface elevation which begins while the hurricane eye is well offshore, days before landfall. The rate of water level rise begins to accelerate as the eye moves across the continental shelf. Hurricane Ike produced a sizable forerunner. During Ike, the water level increase began several days before landfall and reached a measured amplitude in excess of 6 ft above the seasonal mean sea level at the Galveston Pleasure Pier, twelve hours before landfall. Water level data acquired by NOAA also show that the forerunner propagated into Galveston Bay through the tidal passes and into the upper reaches of the Houston Ship Channel with little attenuation.

As observed during Ike, the forerunner can propagate into the bays via the tidal passes. Once, closed, the Bolivar Roads Surge Barrier at the much deeper and more hydraulically efficient Bolivar Roads pass will eliminate subsequent forerunner propagation into the Bays through this particular pass. However, leaving the "back door" open at San Luis Pass, albeit a shallower, less hydraulically efficient pass, will still allow some propagation of the forerunner into West and Galveston Bays. This issue was examined using the simulation of Hurricane Ike, for both present and future sea levels.

Hurricane Ike is the only severe hurricane that has made landfall in the Houston-Galveston region, produced a substantial surge forerunner and peak surge, for which we have high-quality measured data to characterize the hurricane's speed, size intensity, winds and pressures, and the water level response. Hurricane Ike is the best example to use for assessing the ability of a large surge forerunner to propagate into West and Galveston Bays through the San Luis Pass open back door. This is because measured far field wind speed and direction data are available for the Bay region while the hurricane eye is well offshore, during the initial stage of the forerunner development process.

Accurate representation of the far field winds within semi-enclosed bays is critical in attempting to model forerunner propagation into the Bays. The wind and pressure field model that is used to simulate hypothetical hurricanes produces highly structured and idealized wind fields in the far field. The directions and strength of these far field winds tend to somewhat retard surge forerunner propagation into West and Galveston Bays. Some of the more extreme hypothetical hurricanes show less forerunner penetration than the Hurricane Ike simulation, for this reason. This might not reflect reality. In the early stages of forerunner development, measured far field wind data during Ike show variable direction and speed, with much less structure to the wind fields. Without masking the winds in some way in both West and Galveston Bays, the current method of modeling storm surge for hypothetical hurricanes will tend to underestimate surge forerunner propagation into both Bays. Surge forerunner generation and simulation of the surge forerunner in the Houston-Galveston region are discussed in in more detail in the JSU (2018) report (see Chapters 5, 6, 7, 13 and 14).

It is also important that low realistic bottom friction on the continental shelf is used in setting up the storm surge model. Excessive bottom friction will over-damp generation of the forerunner and lead to a significant under prediction of its amplitude along the shoreline. The JSU surge modeling, which is reflected in this report, demonstrated good skill in terms of matching measured peak storm surge values in the Houston-Galveston region, see Chapter 2 of the JSU (2018) report, but it still under predicted the forerunner amplitude.

Figure 4-2 shows the simulated surge forerunner elevation for Hurricane Ike, at a snap shot in time, twelve hours before landfall, when the eye (yellow dot in the figure) is well offshore of the Houston-Galveston region. Wind speed and direction are shown as black vectors. At the open coast near San Luis Pass, the amplitude of the forerunner surge reached an elevation of 5.3 ft above the seasonal mean sea level approximately twelve hours prior to landfall. Such a forerunner amplitude inundates the beach berm on Galveston Island and Bolivar Peninsula, which enables wave action to begin eroding the dunes long before landfall. The forerunner amplitude along the Louisiana coast approaches 7.5 ft.

Figures 4-3 and 4-4 show the change in simulated water surface elevation, with time, for Hurricane Ike at two locations: the first inside West Bay (Figure 4-3), midway between San Luis Pass and the City of Galveston; and the second roughly in the center of Galveston Bay (Figure 4-4), with and without a western section of the coastal spine.

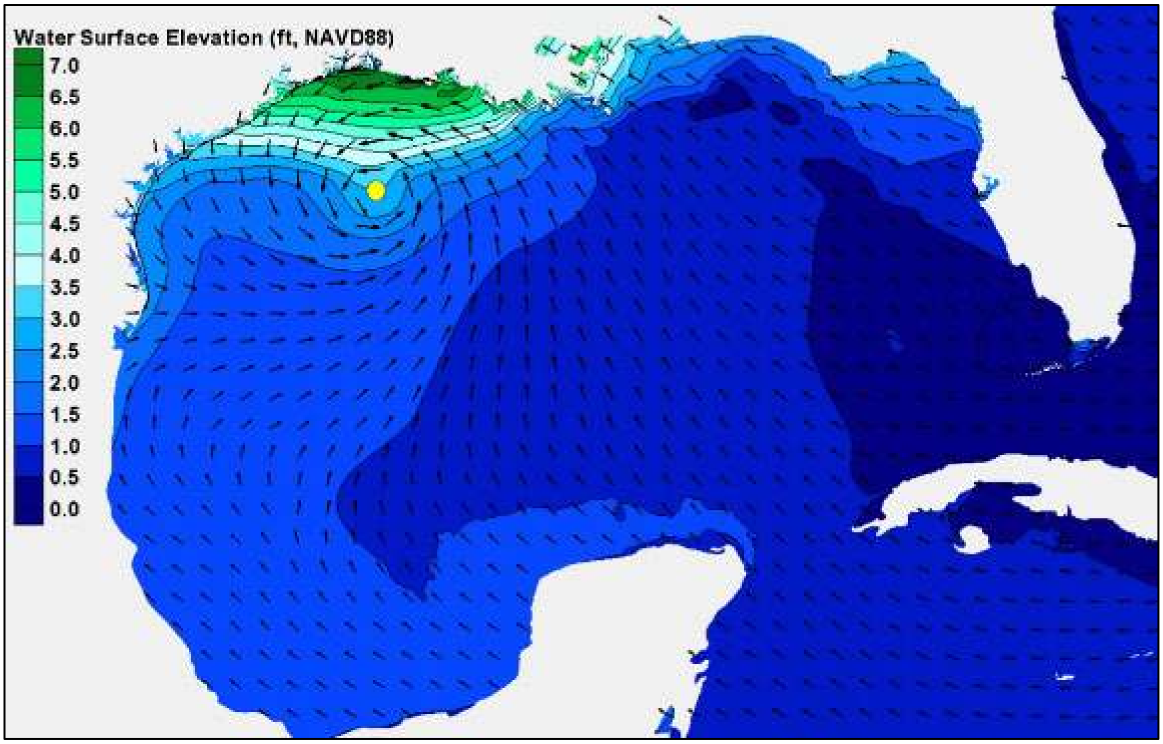

Figure 4-2. Snap-shot of the water surface elevation field associated with the Hurricane Ike surge forerunner, twelve hours prior to landfall

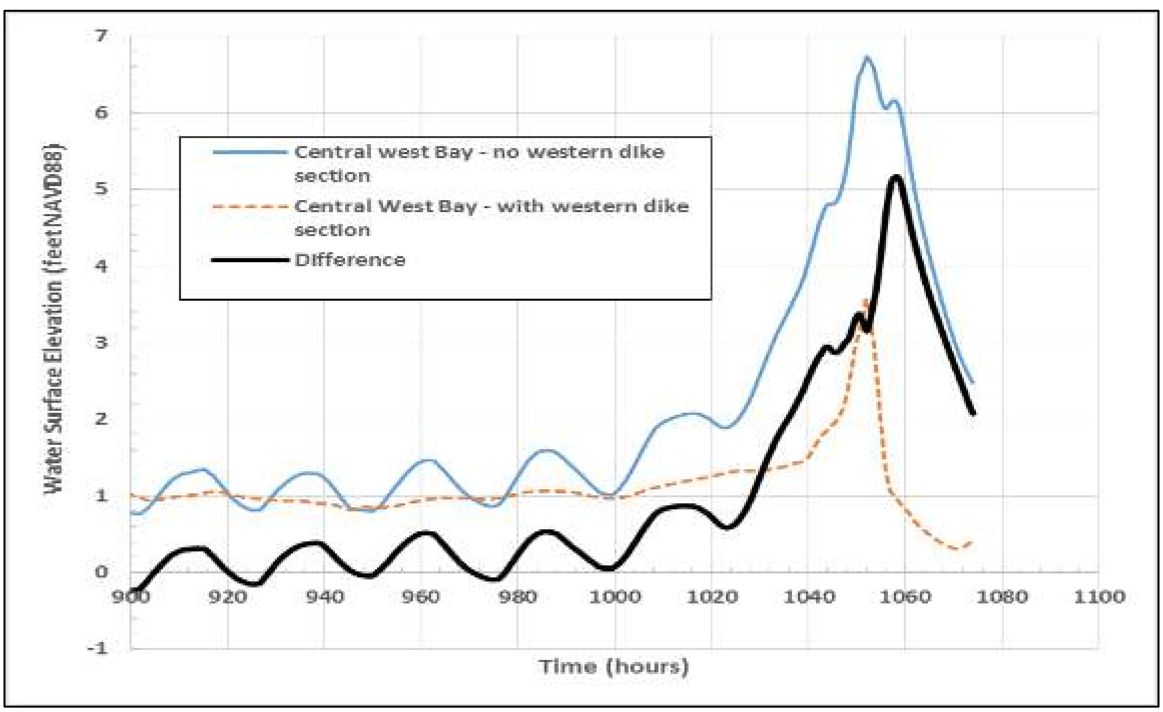

Figure 4-3. Water surface elevation in the center of West Bay, with and without a western section, for Hurricane Ike, present sea level

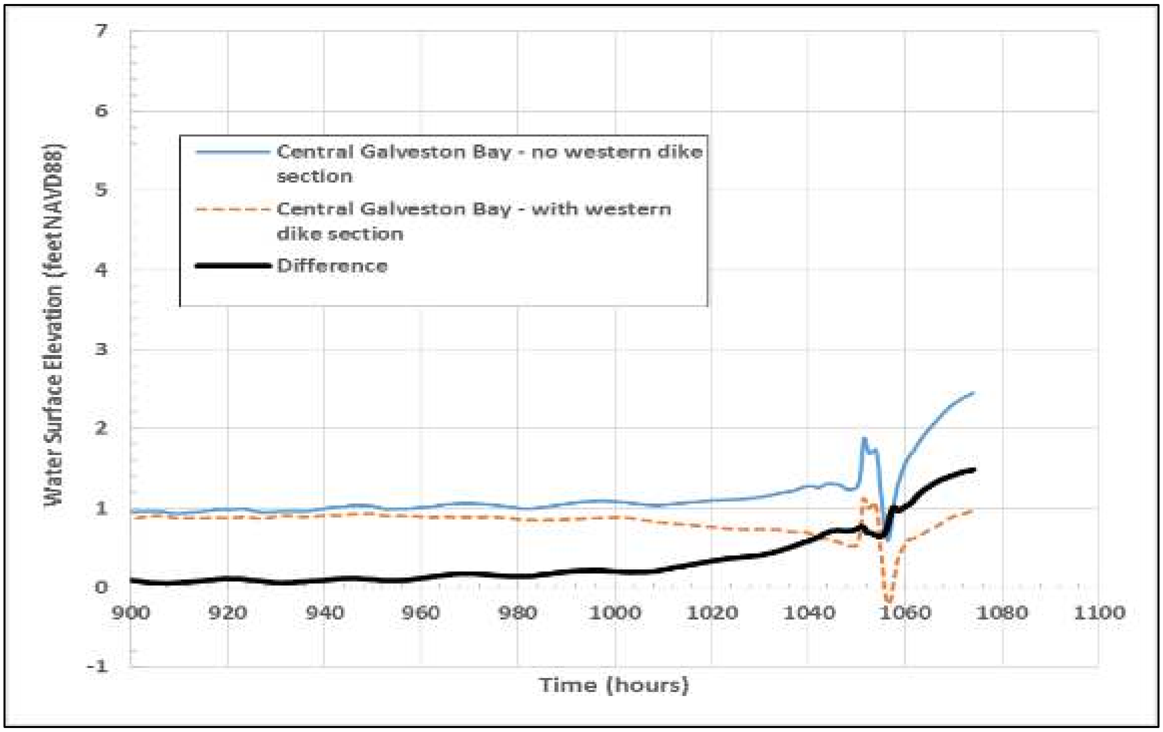

Figure 4-4. Water surface elevation in the center of Galveston Bay, with and without a western section, for Hurricane Ike, present sea level.

Locations in the center of the bays were selected to minimize the influence of local wind, which sets up one side of the bay and sets down the other side, obfuscating the forerunner amplitude. The thin orange dashed curves in both figures show the water surface elevation time series for the 17-ft Ike Dike concept, which has a western section. The thin blue solid curves show the water surface elevation for the coastal spine alignment like the USACE Plan that has no western section. The thick black curve shows the difference between the orange and blue curves; it quantifies the change in water surface elevation due to leaving the “back door” open, i.e., the impact of having no western section.

Prior to hour 1044 of the simulation, the black “difference” curves reflect the influence of forerunner propagation through San Luis Pass. Without the western section, in West Bay, the forerunner surge elevation steadily rises to maximum amplitude of 2.9 ft, 12 hours before landfall. Results indicate some attenuation through the shallow San Luis Pass, from an amplitude of 5.3 ft on the open coast to an amplitude of 2.9 ft inside West Bay. Although additional attenuation occurs as the forerunner propagates from West Bay into Galveston Bay, in Galveston Bay the forerunner also grows steadily in the days prior to landfall and its amplitude reaches 0.7 ft, clear evidence of forerunner propagation from West Bay into Galveston Bay. Results for the Upper Houston Ship Channel, not shown here, are nearly identical to those shown for the center of Galveston Bay. Once inside Galveston Bay, there is little attenuation of the forerunner amplitude, as was observed during the actual Hurricane Ike. For the simulated Hurricane Ike, because of forerunner propagation through an open San Luis Pass, the entire West Bay water level is raised by 2.9 ft, and the entire Galveston Bay water level is raised by 0.7 ft, everywhere, 12 hours before landfall.

As also seen in Figures 4-3 and 4-4, at and after hour 1060 of the simulation, the effect of omitting a western section on peak surge is an increase of approximately 5.2 ft at the central West Bay location and an increase of 1.5 ft at the central Galveston Bay location. The implications of an open "back door" for peak surge and inundation inside the bays are discussed at greater length in the next section.

The Hurricane Ike simulation for future sea level shows that omission of the western section leads to similar results for surge forerunner propagation into West Bay as obtained for the present sea level; a slightly higher hurricane forerunner surge of 3.1 ft twelve hours prior to landfall, and an increase in peak surge of about 5.2 ft. However, in Galveston Bay, the forerunner surge amplitude is 1.2 ft (0.5 ft higher than for present sea level case) and the increase in peak surge is 2 ft (also an increase of 0.5 ft). With the "back door" open, rising sea level apparently reduces the attenuation of, and increases the propagation efficiency of, the surge forerunner from West Bay into Galveston Bay. This leads to higher forerunner surge and peak surge values in Galveston Bay. The effects of higher future sea level on peak surge and inundation inside the bays are discussed at greater length in a subsequent section.

Uncertainty in Understanding and Modeling the Hurricane Surge Forerunner

We believe that the importance and prediction of the hurricane surge forerunner is underestimated in the work that has been done to arrive at the USACE Plan. Generation of the hurricane surge forerunner is not a completely understood process; and accurate simulation of the forerunner is challenging. Relatively little is known regarding the forerunner amplitude on the Texas coast, specifically, the distribution that characterizes its probability of occurrence. There is some understanding of the dependencies of forerunner amplitude on hurricane characteristics. Unfortunately, we only have observed data for a single major hurricane that produced a substantial forerunner and made landfall in the region, Hurricane Ike.

The maximum possible amplitude for a surge forerunner is unknown. During Ike, the forerunner amplitude reached 6.5 ft at the Galveston Pleasure Pier, and apparently 7.5 ft or more along the Louisiana coast. Hurricane Ike was a very large hurricane, but moderate in intensity. Ike was only a Category 2 storm on the Saffir-Simpson wind intensity scale for hurricanes. Research by JSU and others indicates that the forerunner magnitude grows as hurricane size increases, as intensity increases, and as forward speed decreases; forerunner amplitude also appears to be somewhat sensitive to storm track. Ike had an average forward speed and approached from the southeast. JSU research suggests that the worst scenario for forerunner generation appears to be a large, intense, very slow-moving hurricane that approaches from the south or south-southeast direction. More information about forerunner generation is provided in Chapters 5, 6 and 14 of the JSU (2018) report.

In light of uncertainties regarding the surge forerunner, conservatism is warranted in how the forerunner is considered and treated in formulating the USACE Plan. Conservatism also is warranted in light of the accuracy of the USACE surge modeling in simulating the forerunner and its amplitude. Validation results for the USACE storm surge modeling for Hurricane Ike reflect the difficulty, as shown in Annex 1 to Appendix D of USACE (2020). Results indicate that the surge model has limited skill in simulating the forerunner. The surge model consistently under predicts the steady water level build-up that occurs for two days before landfall; and the maximum amplitude is under predicted by approximately 1.5 to 2 ft (a 20% to 30% under prediction).

Under prediction of the hurricane surge forerunner leads not only to understating its role in increasing flooding in the Bays due to forerunner propagation through the open “back door,” but also to understating its role in eroding the dune system. Under prediction of the forerunner’s amplitude will underestimate how quickly the berm is inundated by the forerunner, which then subjects the dunes to the direct erosive action of waves. The net result is that under prediction of the forerunner leads to under prediction of dune erosion, and for the weak dunes in the USACE Plan, can lead to an underestimate of the storm surge that flows into the bays over the flattened dunes.

In the USACE surge modeling, a higher bottom friction coefficient was applied on the continental shelf, to improve model stability. JSU researchers found that such a choice overdamps generation of the forerunner, leading to underestimates of its amplitude. Therefore, there is good reason to believe that the forerunner being simulated by the USACE for all hurricanes, including those most critical to the design and performance of the USACE Plan, are under predicted. JSU researchers used a smaller bottom friction coefficient on the shelf, a reasonable value for muddy bottoms, and were able to achieve a more accurate simulation of the forerunner for Hurricane Ike, but still with an under prediction.

We recommend that the USACE pursue model improvements that lead to better skill in simulating the forerunner. We recommend validation of model skill in terms of how well the forerunner build-up and maximum amplitude is simulated for Hurricane Ike, and perhaps other major land falling hurricanes in southwest Louisiana where the potential for a significant forerunner exists, as well. We recommend using the improved surge model to examine the distribution of forerunner amplitudes for the Texas coast, including an estimate of the maximum forerunner amplitude that is possible. We recommend using the improved model in the investigation into quantifying benefits of a western section of the coastal spine, and in the beach/dune erosion modeling. Improved understanding of the forerunner climate will undoubtedly prove beneficial in formulating a plan to guide operations of gate systems at both Bolivar Roads Pass and San Luis Pass.

Influence of Flanking of the USACE Plan Coastal Spine by the Main Storm Surge

Without a western section of the coastal spine, as the hurricane eye approaches landfall and as the forerunner development period transitions into development of the main surge, the storm surge continues to propagate into West Bay via San Luis Pass and then over Follets Island as well once the island becomes inundated. Even for relatively frequent hurricane events, omission of the western section leads to inundation within communities on western and central Galveston Island, inundation that is avoided with a western section in place. The adverse effects of flanking are much more widespread for more severe hurricanes.

The effect of surge flanking the western end of the coastal spine in the USACE Plan is illustrated below using both peak surge maps and inundation maps. Colored shaded contour maps of peak surge depict the peak storm surge elevation calculated at every computational point in the ADCIRC storm surge model domain, without regard to when the peak surge elevation occurred during the simulation. These peak surge maps do not represent snap shots in time. To illustrate the spatial extent of inundation, both with and without a western section, a “transparent” peak surge map is superimposed over a background satellite image to create an inundation map that shows what terrain is being inundated.

Pairs of maps are presented in the series of figures below. The map in the top panel of each figure shows the peak surge (or inundation) map for the Ike Dike concept, which has a western section. The map in the bottom panel shows results for the alignment that is similar to the USACE Plan coastal spine, which omits the western section. Peak surge and inundation maps are shown for three of the storms listed in Table 4-1: Hurricane Ike, Storm 023, and Storm 019. The simulation of Hurricane Ike produced a peak surge of approximately 10 ft NAVD88 at San Luis Pass and about 14 ft NAVD88 at the City of Galveston. Storm 023 is a hypothetical hurricane that approximately produced the 100-yr water level at San Luis Pass of 14 ft NAVD88; and Storm 019 is a hypothetical hurricane that approximated the 10-yr water level at San Luis Pass, 7 ft NAVD88.

Figure 4-5 shows peak storm surge maps for Hurricane Ike, for present sea level, with a western section (top panel) and without a western section (bottom panel). Results clearly show that the peak surge is much higher in West Bay with the “back door” open. The increases in peak surge are greatest near San Luis Pass; and they decrease from west to east within West Bay. Without the western section, peak surge at the west end of Galveston Island is 5 to 5.5 ft higher than the peak surge with the western section. The effect of leaving the “back door” open on peak surge extends to the City of Galveston, where the peak surge is 1.5 to 2 ft higher without the western section. Leaving San Luis Pass open influences the design of the Galveston Ring Barrier. The increase in peak surge with the “back door” open is not limited to West Bay. Increases also are evident in Galveston Bay; however, the magnitude of the increase in peak surge is less in Galveston Bay than it is in West Bay. Peak surge differences in Galveston Bay, approximately 1 to 1.5 ft in most places, and are slightly smaller than differences at the City of Galveston.

As illustrated in Figure 4-6, for Hurricane Ike, present sea level, some of lowest-lying areas on western Galveston Island closest to West Bay are inundated even with the western section in place (top panel in Figure 4-6). However, without the western section, inundation of terrain surrounding West Bay is much more widespread; and, western Galveston Island is nearly completely inundated (circled region in the bottom panel of Figure 4-6).

Figure 4-7 shows inundation maps for Hurricane Ike, present sea level, for eastern Galveston Island. Some of lowest-lying areas on eastern Galveston Island and a community on the north side of West Bay are inundated even with the western section in place. However, without the western section, inundation of the circled eastern Galveston Island communities is complete; multiple communities on the north side of West Bay are inundated, as are parts of the City of Galveston, including the airport (see the circled areas in the bottom panel of Figure 4-7). Note that these simulations do not include the Galveston Ring Barrier. Some of the circled areas in Figure 4-7 are included in the Economic Reach 37, which experiences high residual damages for the USACE Plan (see Chapter 6 to locate the boundaries of Reach 37).

Figure 4-8 shows peak surge maps for Storm 023, present sea level, with a western section (top panel) and without a western section (bottom panel). Results show that the peak surge is, again, much higher in West Bay with the “back door” open. Again, as is seen for all the storms that were simulated, the increases in peak surge are greatest nearer San Luis Pass and they decrease from west to east in West Bay. Without the western section, peak surge at the west end of Galveston Island is 7 ft higher than the peak surge with the western section in place. At the City of Galveston, the peak surge is 1 ft higher without the western section. Increase at the City of Galveston influences the design of the Galveston

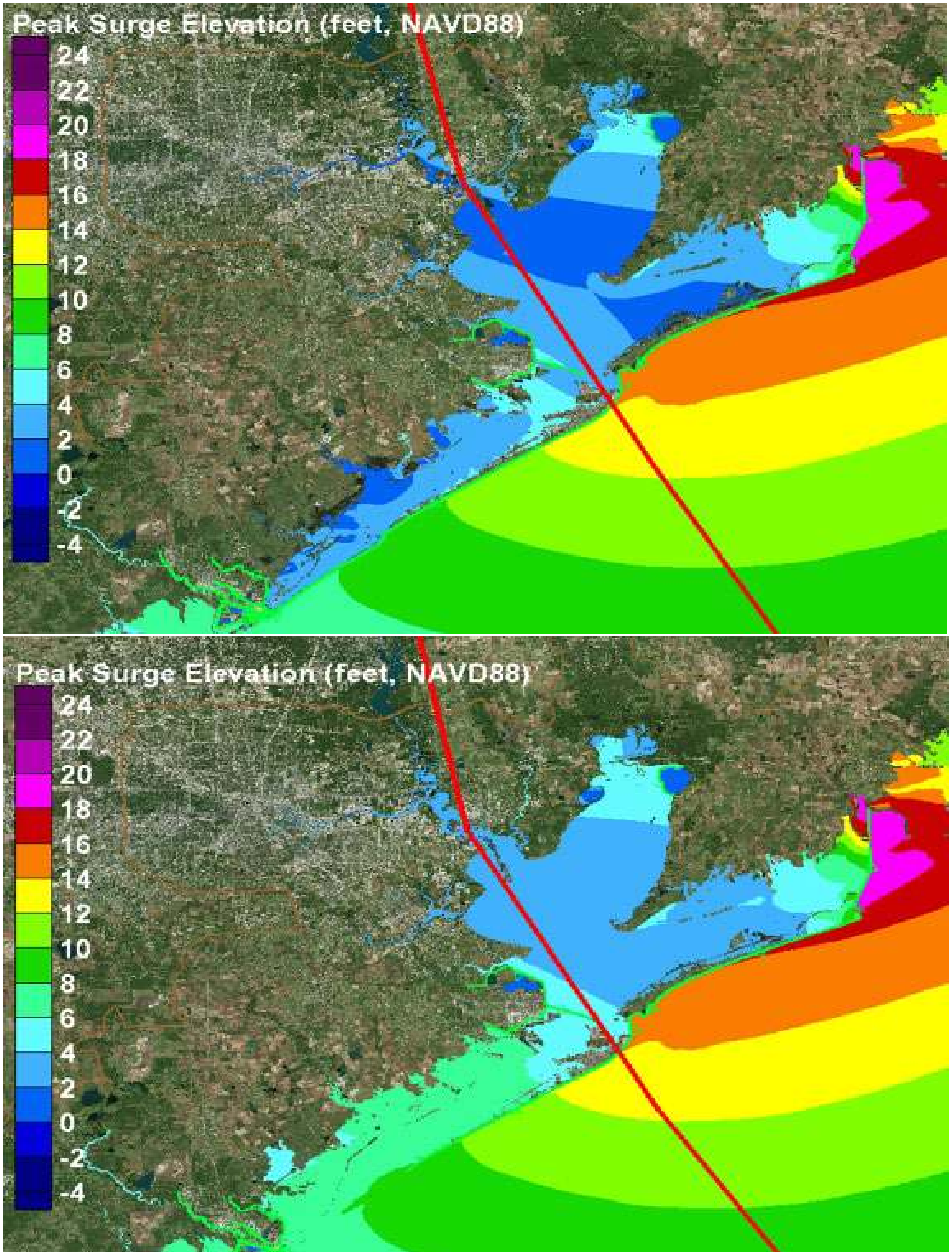

Figure 4-5. Peak surge maps for Hurricane Ike, present sea level, for the Ike Dike coastal spine concept having a western section (top panel) and an alignment similar to the USACE Plan that does not have a western section (bottom panel).

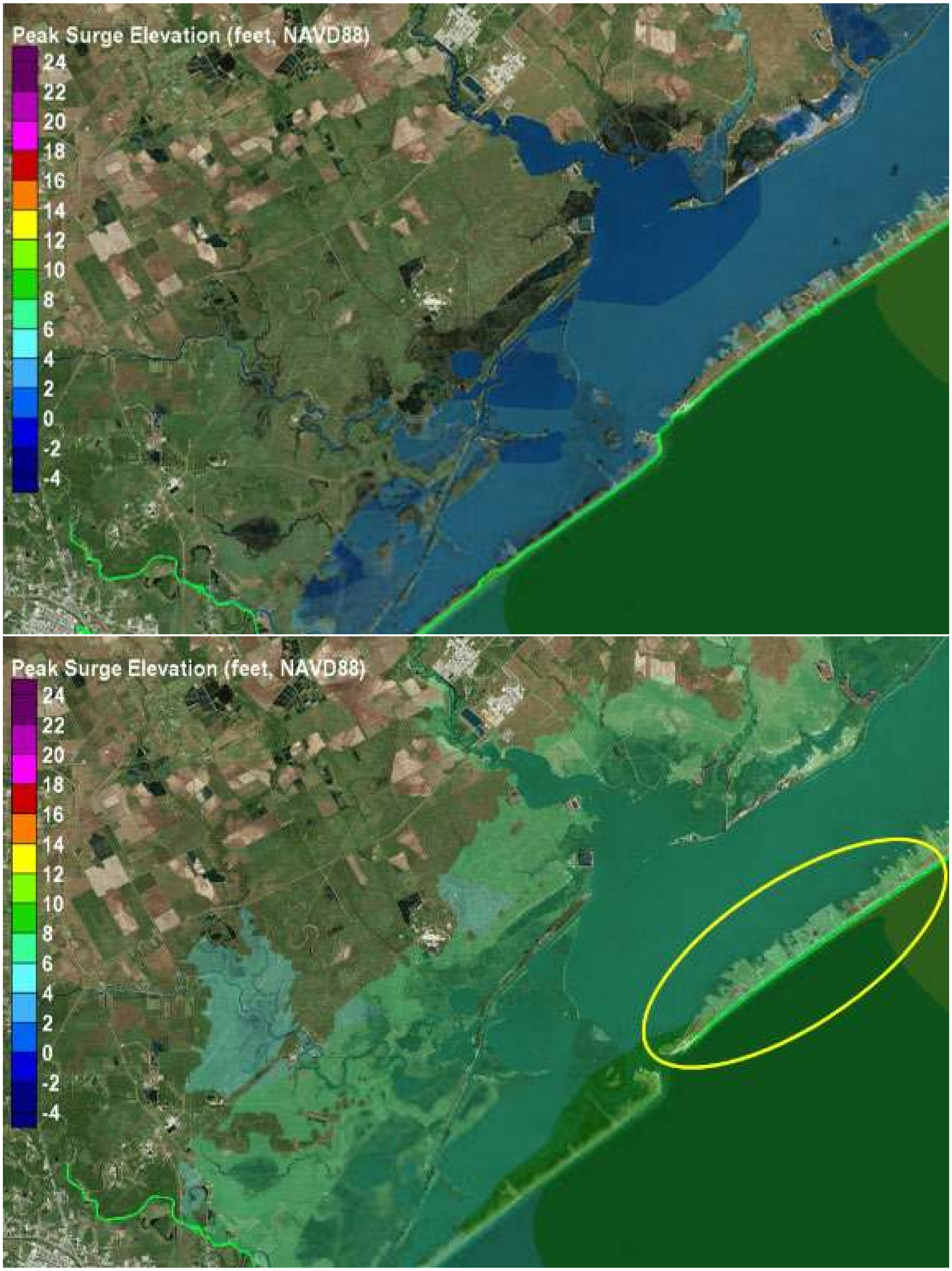

Figure 4-6. Inundation maps in near San Luis Pass, for Hurricane Ike and present sea level, for the Ike Dike coastal spine concept having a western section (top panel) and an alignment similar to the USACE Plan that does not have a western section (bottom panel).

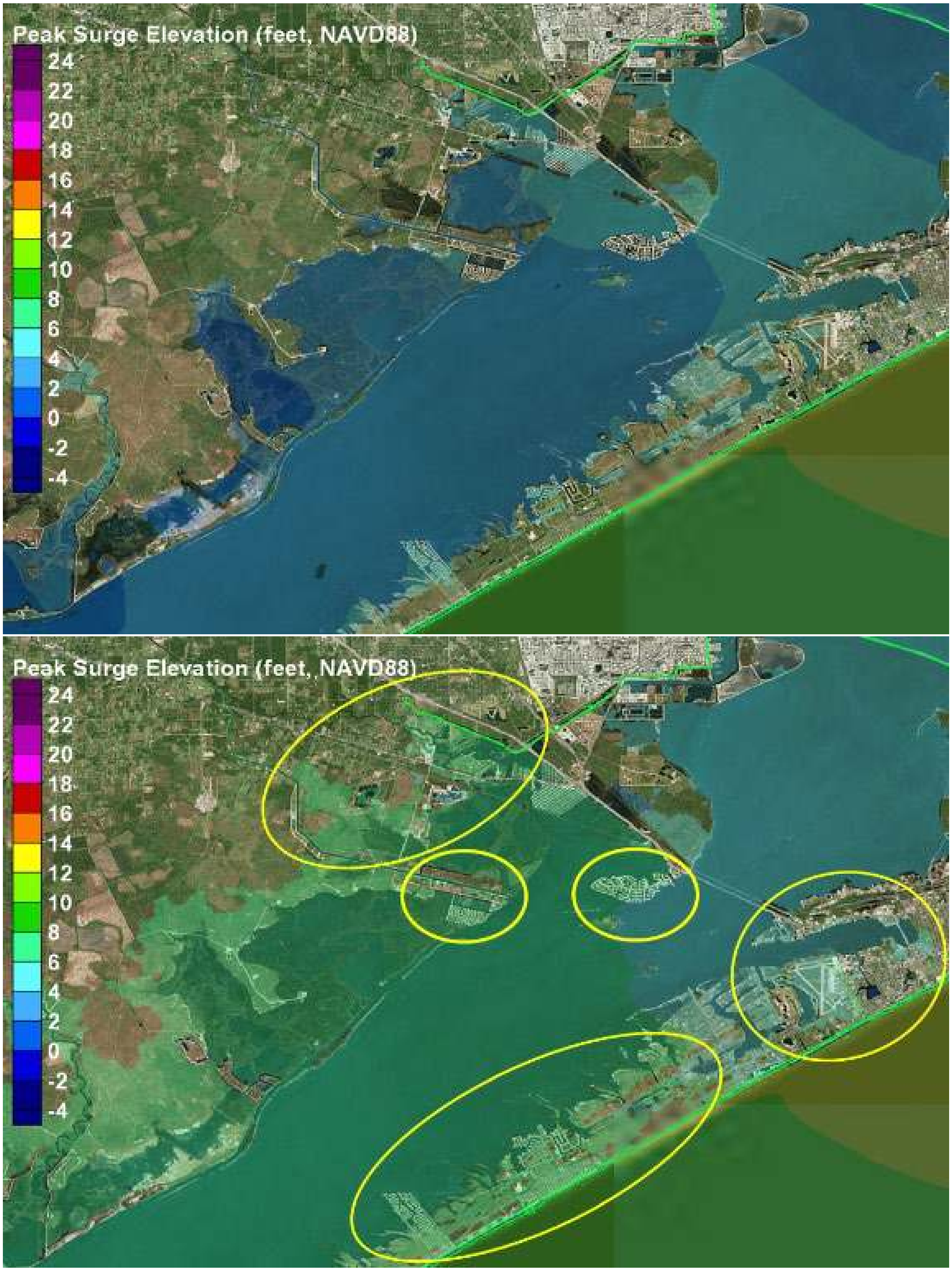

Figure 4-7. Inundation maps in eastern West Bay, for Hurricane Ike and present sea level, for the Ike Dike coastal spine concept having a western section (top panel) and an alignment similar to the USACE Plan that does not have a western section (bottom panel).

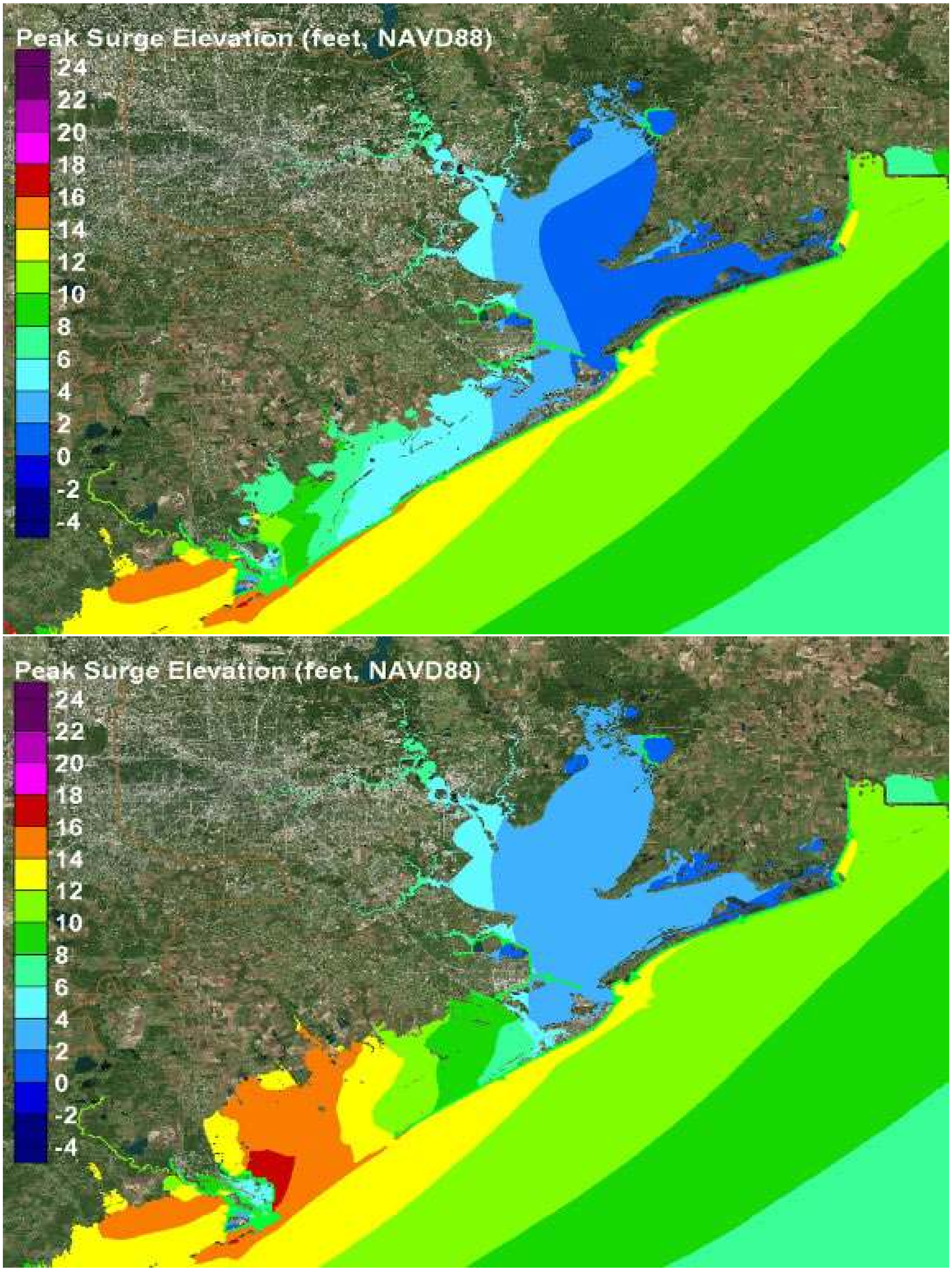

Figure 4-8. Peak surge maps for Storm 023, present sea level, for the Ike Dike coastal spine concept having a western section (top panel) and an alignment similar to the USACE Plan that does not have a western section (bottom panel).

Ring Barrier. Increases in peak surge also are evident in Galveston Bay; however, the magnitude of the increase in peak surge is less in Galveston Bay than it is in West Bay. Peak surge differences in parts of Galveston Bay are comparable to the differences at the City of Galveston, approximately 1 ft in places, less along the western side of the Bay.

For Storm 023, present sea level, some of lowest-lying areas on western Galveston Island closest to West Bay are inundated with the western section in place (upper panel of Figure 4-9). However, without the western section, inundation of terrain surrounding West Bay is much more widespread and western Galveston Island is completely inundated (see the circled area in the bottom panel of Figure 4-9). Inundation is more severe for Storm 023 than for Hurricane Ike. Without the western section, a LNG complex near Freeport is significantly inundated as are the petro-chemical complexes along Chocolate Bayou; both facilities are circled in the bottom panel of Figure 4-9. The region shown in Figure 4-9 is included in Economic Reach 4, which has high residual damage for the USACE Plan.

For Storm 023, present sea level, some of lowest-lying areas on eastern Galveston Island are inundated with the western section in place (see top panel in Figure 4-10). However, without the western section, inundation of the indicated eastern Galveston Island communities is complete, multiple communities on the north side of West Bay are inundated, as are parts of the City of Galveston, including the airport (see the circled areas in the bottom panel of Figure 4-10). Two of the circled regions shown in Figure 4-10 are included in Economic Reach 37, which has high residual damage for the USACE Plan.

Leaving the “back door” open leads to increased flooding and inundation on Galveston Island even for relatively frequent, weaker, hurricane events, like Storm 019. Storm 019 was selected to replicate the 10-yr average recurrence interval water level at the entrance to San Luis Pass, a peak surge of 7 ft NAVD88. Figures 4-11 and 4-12, show the increase in inundation that occurs for Storm 019, present sea level, with the “back door” open (top panels) and the “back door” closed (bottom panels). Figures 4-11 and 4-12 show the differences in inundation for western and central Galveston Island, respectively. The USACE Plan provides very little protection for parts of western Galveston Island that lie outside the Galveston Ring Barrier.

Influence of Sea Level Rise on Increased Peak Surge and Inundation Associated with Flanking

In general, rising sea level will increase flood risk throughout the Houston-Galveston region, both with and without a western section. Low-lying areas and areas having low topography gradients are most susceptible to increases in sea level. Leaving the “back door” open increases the susceptibility of the most vulnerable areas to flooding as sea level rises. In addition to all those areas around West Bay, there also appear to be areas around the periphery of Galveston Bay where surge levels and inundation are exacerbated because of leaving the open “back door.”

For example, for Hurricane Ike and the future sea level scenario, a number of areas in the City of Galveston are exposed to inundation, which otherwise, would not be inundated with the western section in place (see the circled area in Figure 4-13). Most or all of these areas are included inside the Galveston Ring Barrier, but its design elevation for the future sea level rise scenario is influenced by leaving the “back door” open.

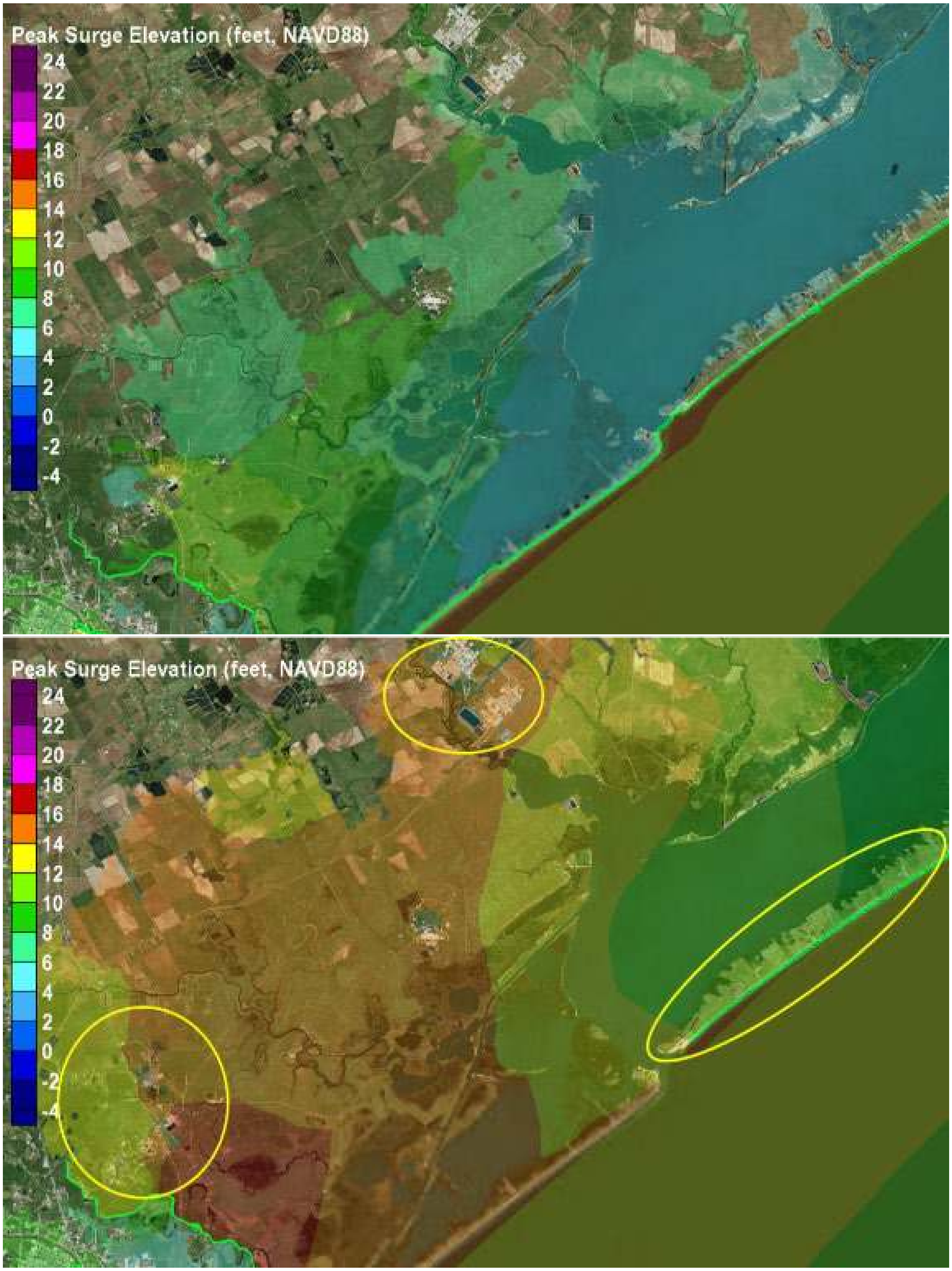

Figure 4-9. Inundation maps near San Luis Pass, for Storm 023 and present sea level, for the Ike Dike coastal spine concept having a western section (top panel) and an alignment similar to the USACE Plan that does not have a western section (bottom panel).

Figure 4-10. Inundation maps in eastern West Bay, for Storm 023 and present sea level, for the Ike Dike coastal spine concept having a western section (top panel) and an alignment similar to the USACE Plan that does not have a western section (bottom panel).

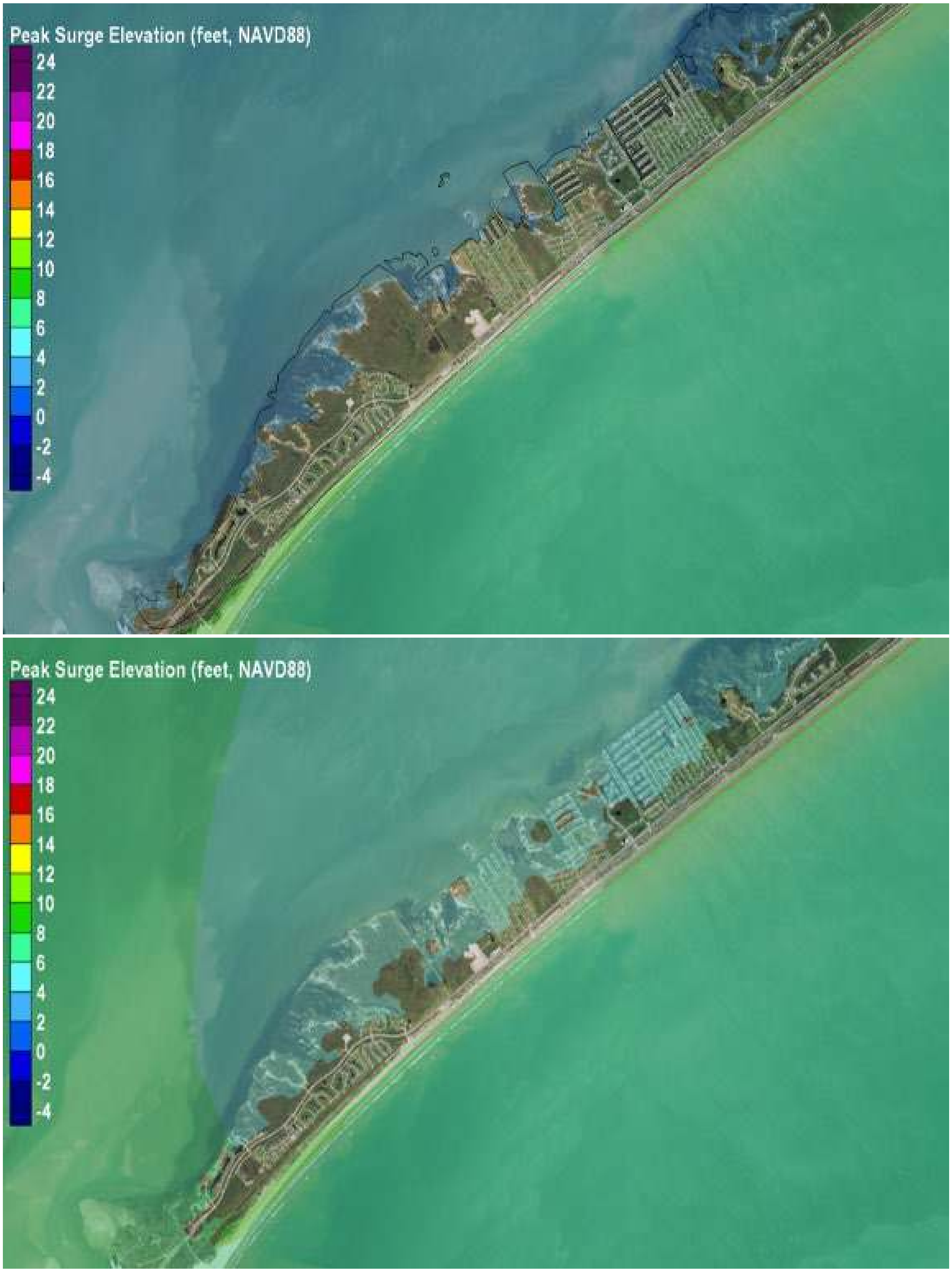

Figure 4-11. Inundation maps for western Galveston Island, for Storm 019 and present sea level, for the Ike Dike coastal spine concept having a western section (top panel) and an alignment similar to the USACE Plan that does not have a western section (bottom panel).

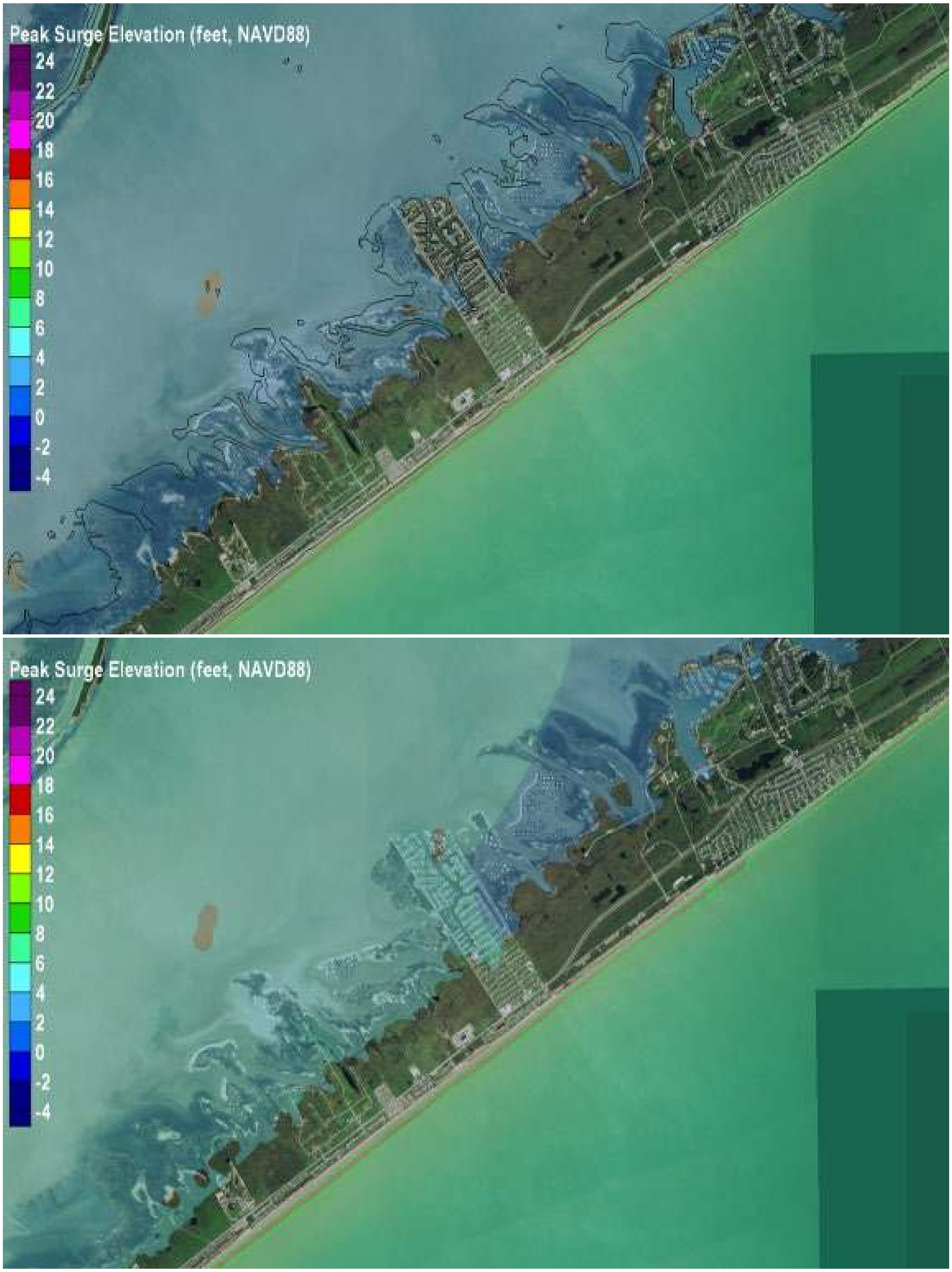

Figure 4-12. Inundation maps for central Galveston Island, for Storm 019 and present sea level, for the Ike Dike coastal spine concept having a western section (top panel) and an alignment similar to the USACE Plan that does not have a western section (bottom panel).

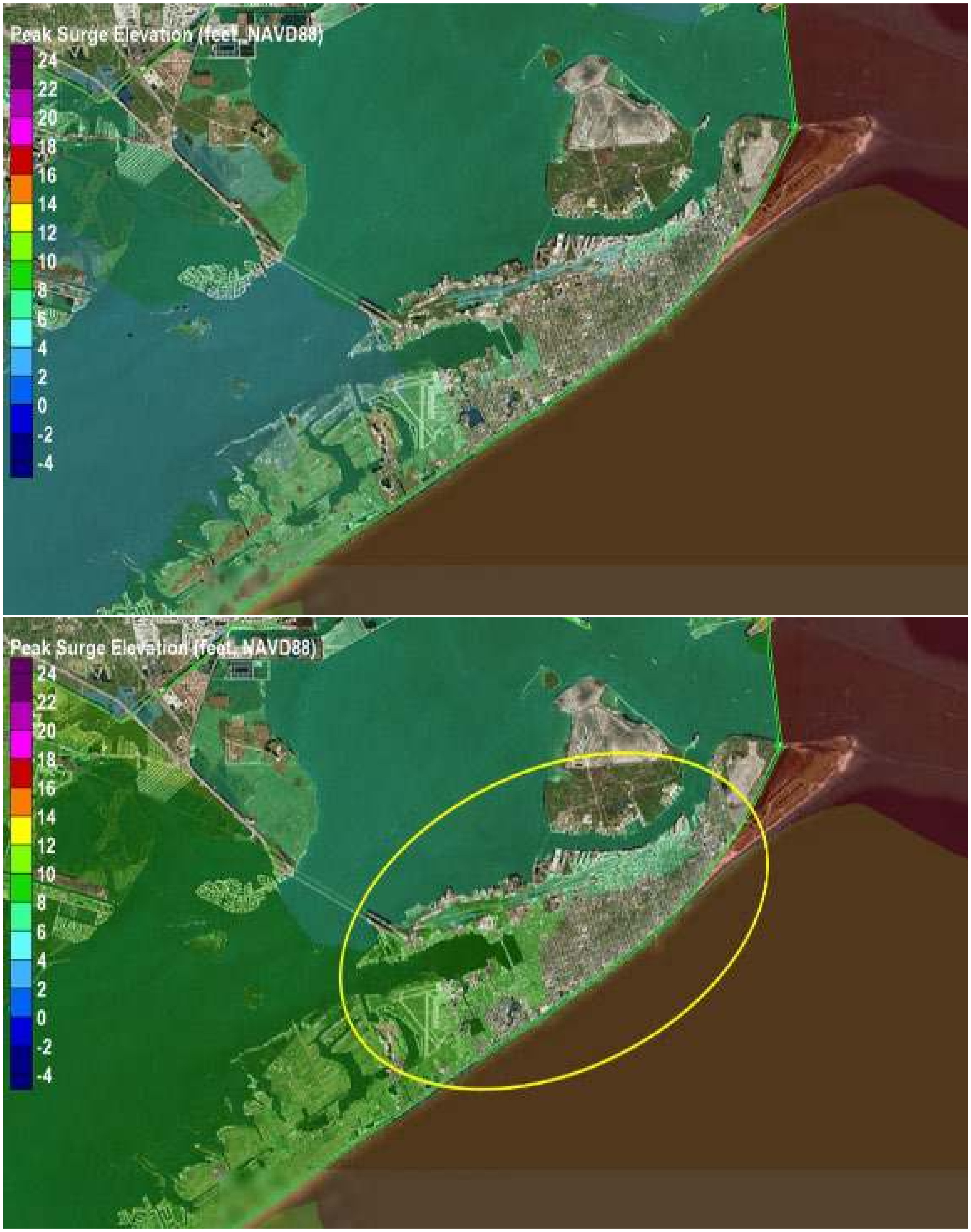

Figure 4-13. Inundation maps for the City of Galveston, for Hurricane Ike and future sea level, for the Ike Dike coastal spine concept having a western section (top panel) and an alignment similar to the USACE Plan that does not have a western section (bottom panel).

There also are similarly affected areas along the western shoreline of Galveston Bay. For Hurricane Ike, and the future sea level scenario, parts of the town of San Leon, adjacent to Dickinson Bay, are inundated (circled area in the bottom panel of Figure 4-14) when the "back door" is left open, which are not inundated with the western section in place (top panel of Figure 4-14). Even small changes in peak surge levels that are caused by leaving the "back door" open can induce inundation and damage inside Galveston Bay.

A similar influence is seen along the eastern shoreline of Galveston Bay. For Hurricane Ike, and the future sea level scenario, the town of Oak Island is inundated (circled area in the bottom panel of Figure 4-15), which does not occur with the western section in place (see the top panel of Figure 4-15). With rising sea level, the adverse effects of leaving the "back door" open do not appear to be restricted to West Bay or the western side of Galveston Bay.

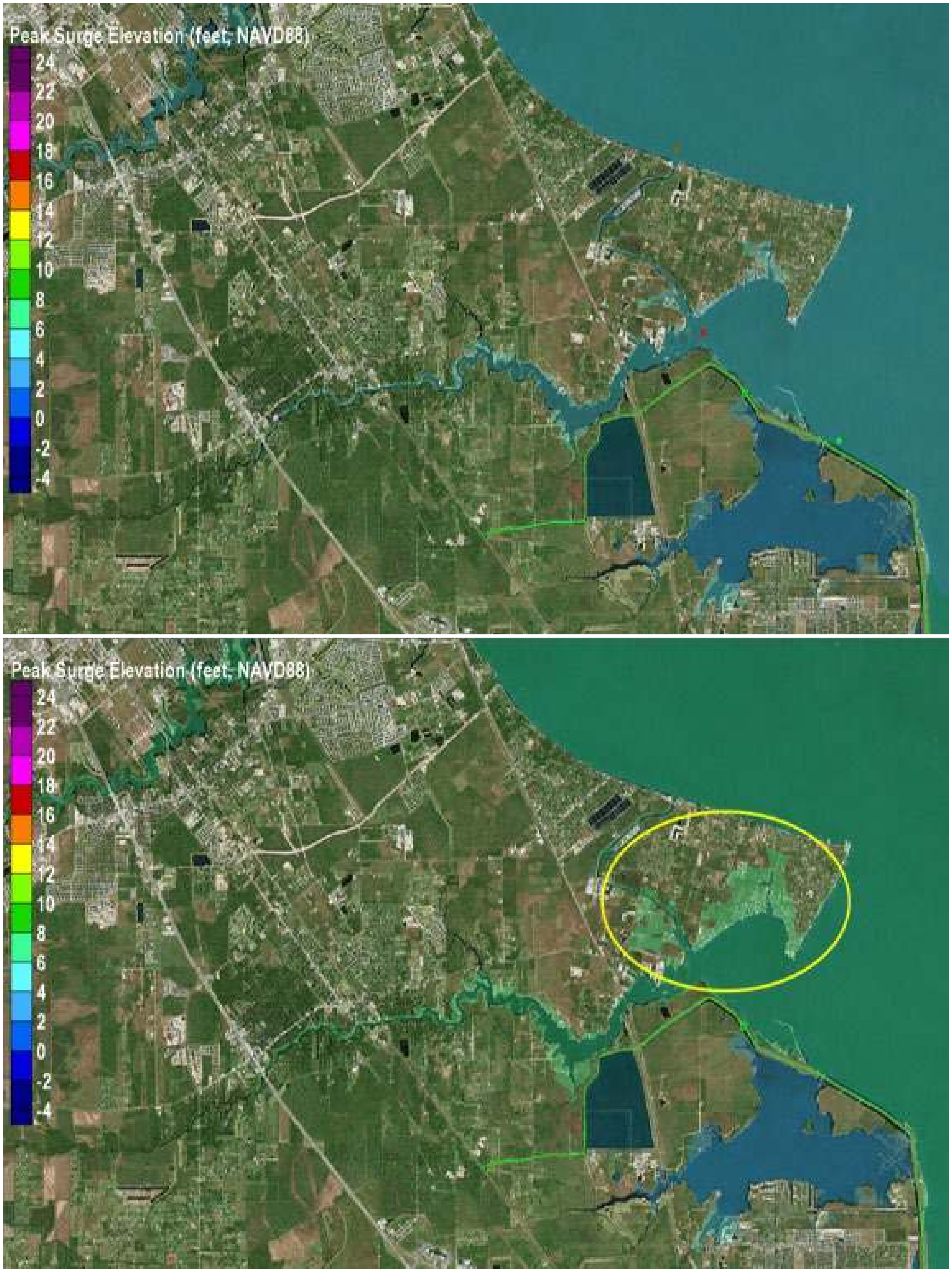

Figure 4-14. Inundation maps for the town of San Leon, for Hurricane Ike and future sea level, for the Ike Dike coastal spine concept having a western section (top panel) and an alignment similar to the USACE Plan that does not have a western section (bottom panel).

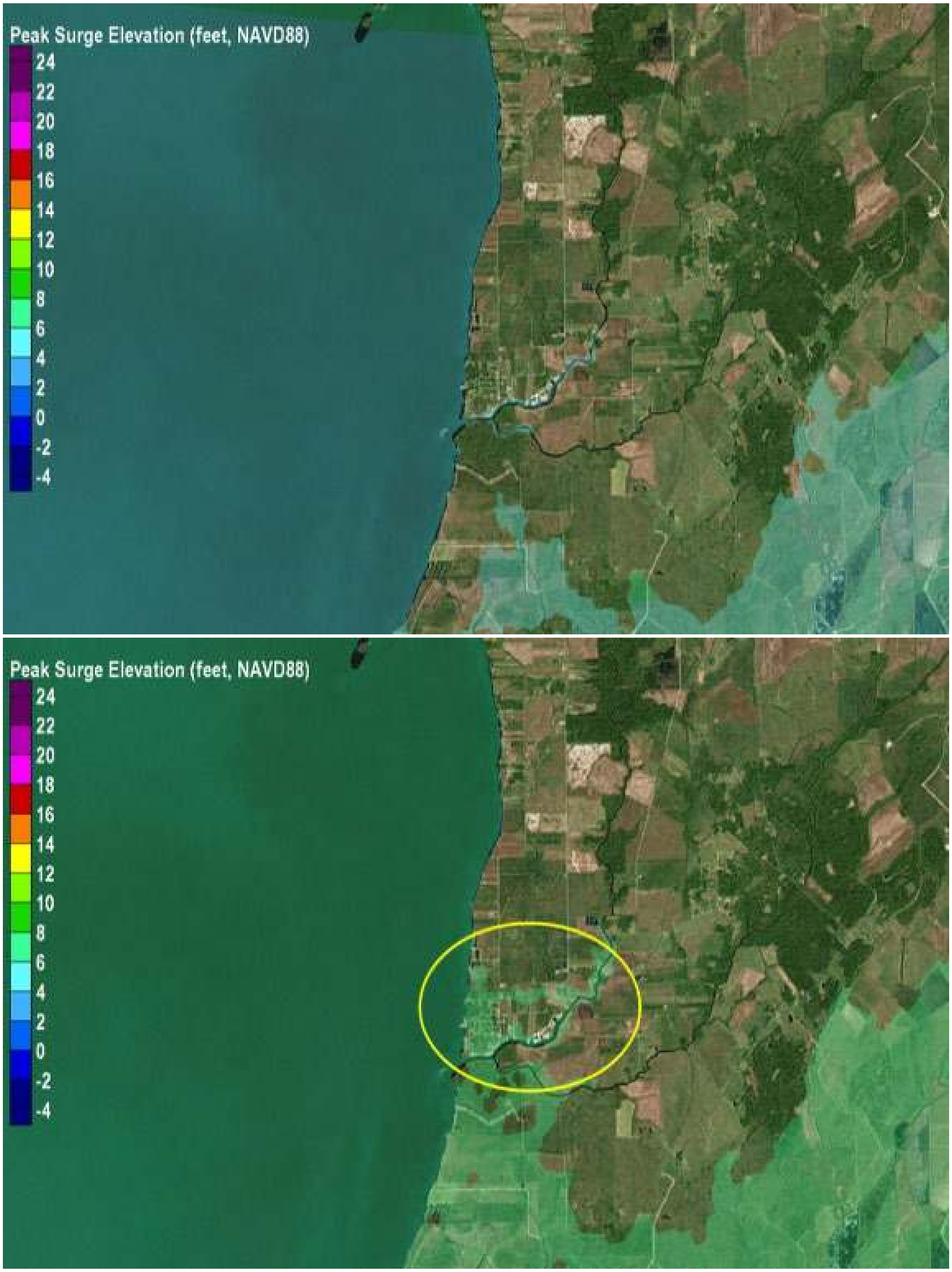

Figure 4-15. Inundation maps for the town of Oak Island, for Hurricane Ike and future sea level, for the Ike Dike coastal spine concept having a western section (top panel) and an alignment similar to the USACE Plan that does not have a western section (bottom panel).

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Chapter 5. Galveston Ring Barrier and Seawall

Introduction

Instead of the proposed Ring Barrier, we recommend consideration of a design approach that incorporates city functions into the protection using urban landscape architecture best practices. Because much of the surge protection from sea level rise probably won't be needed for a number of years, it might be best to take an adaptive management approach that incorporates actual rates of increase of threats, changes in the built and natural environment, and new technologies in an evolving protection scheme aimed at defending the City of Galveston from increasing nuisance flooding caused by higher tides and increased rainfall as well as from major surge events. It is important to integrate major surge protection with protection from the issue of ever-increasing nuisance flooding. Galveston will see nuisance flooding much more often as sea level and associated king tides increase. And it will see nuisance flooding much more often than major surge events from hurricanes. A ring barrier that requires the securing of many road, railroad and bayou gates is not feasible as a defense against constant small floods. Implementing the barrier would most likely be more disruptive than the small flood itself.

We recommend that the USACE continue to work closely with landscape architects, City departments, and local stakeholders to optimize implementation and quality of the solution. It appears that considerable additional engineering analyses and design work remain, in order to develop a technically sound, well-coordinated barrier and pump system, that meshes well with the urban setting and watershed within which it will be built. A goal should be to use fewer unappealing concrete walls; and, where walls are required, incorporate them into the urban landscape as unobtrusively as possible.

While we support a different design concept, even with a coastal spine in place, there is a residual risk of flooding from the bay side due to internal surge generation within the Bay and to the low elevation of the City adjacent to the Bay. The present USACE coastal protection strategy, as discussed in Chapter 2, provides little protection so Bay defenses have to be stronger. Should the coastal defenses be improved as argued in this response, the Bay measures could be much less intrusive and costly.

The USACE has developed its ring concept and it is an approach to providing bay-side protection so we will review it in this chapter. We do have concerns with the Ring Barrier's elevation, its composition and intrusiveness, and its performance for higher future sea level. The Ring Barrier's footprint in shown in Figure 5-1.

Figure 5-1. Footprint and features of the proposed Galveston Ring Barrier

The Galveston Seawall, which forms the Gulf side of the Ring Barrier, is to be raised to an elevation of 21 ft. The rest of the Ring Barrier is presently comprised of concrete floodwalls (inverted T-walls) having a crest elevation of 14 ft, with retractable navigation gates and environmental gates that open into Offatts Bayou. The USACE Plan includes a number features to promote internal drainage and retractable gates across roads and rail lines. Detached breakwaters are being considered, where the bay side of the Ring Barrier is most exposed to waves generated within Galveston Bay. The apparent purpose of the breakwaters is to reduce wave energy that reaches the floodwall, reducing wave overtopping to acceptable levels. As part of the Plan, a series of pump stations are to be located along the bay side of the Barrier. The pumps evacuate water that accumulates inside the Ring Barrier, discharging it over the floodwall and into the bay. In general, the City has to get the water near the barrier (i.e. near the pump stations) – the New Orleans problem. This could be a problem in Galveston if the interface with the City's interior drainage system is not well coordinated, planned and designed. All figures and tables presented in this chapter were extracted from the Feasibility Report.

Figure 5-2 shows the terrain contours of the watershed inside the Ring Barrier. The eastern half of the interior watershed slopes toward the bays; the western half is quite low in elevation and very flat. Consequently, the eastern half includes rather well drained areas, while the western half includes the poorly drained near Offatts Bayou.

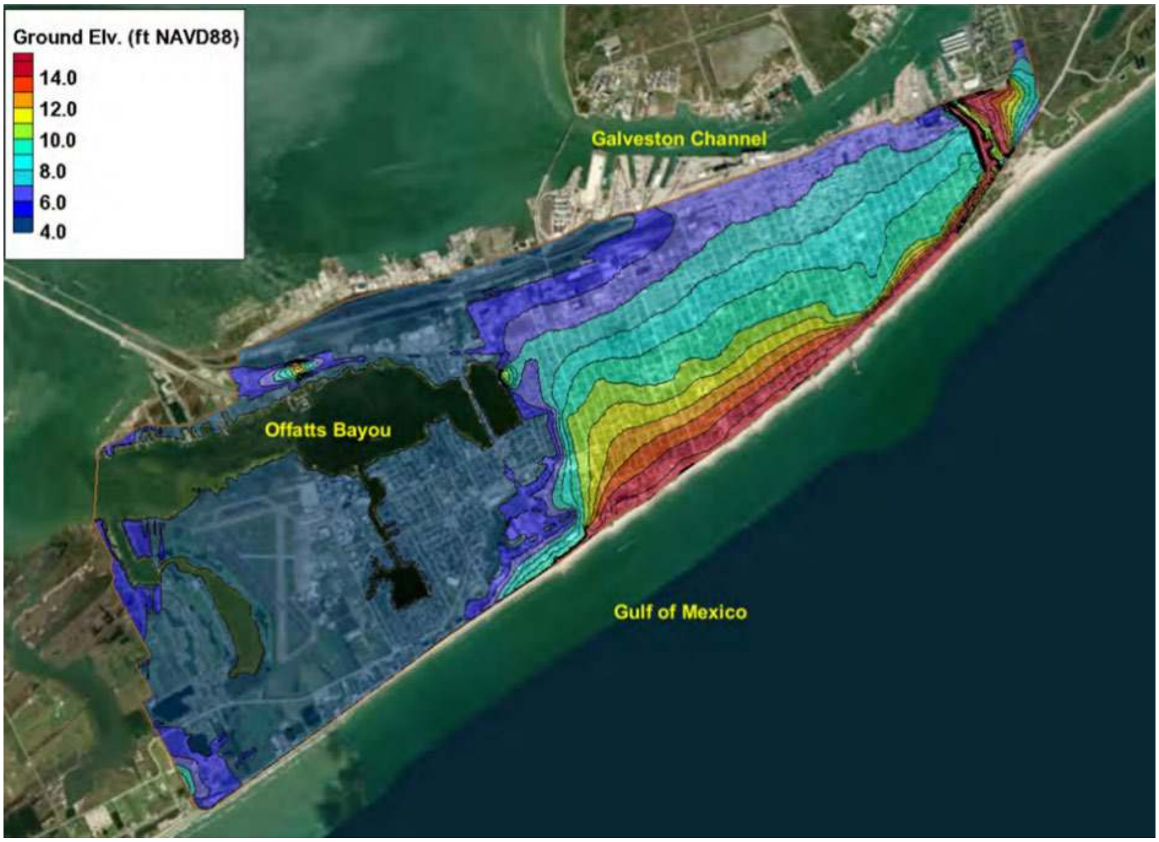

Figure 5-2. Ground elevation contours inside the Ring Barrier

Design of the western half is complicated because of the flat low topography and numerous flows into a gated Offatts Bayou.

Figure 5-2 provides a clear illustration of just how vulnerable the City is to flooding from the bay side, even with the USACE Plan in place. The with-project 100-yr water surface elevations (WSE) on the bay side of the City of Galveston range from 10 to 12 ft NAVD88 for present sea level. They are estimated to be approximately 2 ft higher (12 to 14 ft) for the intermediate-rise future sea level scenario. Areas in the City that are lower than the yellow-shaded area shown in Figure 5-2 are inundated for a WSE of 11 ft, which is nearly the entire City except for the small higher areas immediately adjacent to the Seawall.

Overall Approach to Design and Implementation

The overall approach being taken by the USACE to design and implement the Ring Barrier and Seawall improvements is unclear. The current design for both components was done for present sea level. However, the design standard stated in the Feasibility Report seems to include consideration of future sea level, using the intermediate rate-of-rise scenario. This future sea level scenario was considered in designing all the gate systems included in the USACE Plan (the Bolivar Roads Storm Surge Barrier and the wall/gate systems at the entrances to Clear Lake and Dickinson). The Feasibility Report mentions raising the elevation of the Ring Barrier from 14 ft to 18 ft in the future to accommodate rising sea level. What about the Seawall? What pumping capacities are required in the future, which are dependent upon future elevations of not only the Ring Barrier but also the Seawall.

Does the approach involve design and construction for present sea level, and then adapting the entire system at some future time as sea level rise unfolds? Much of the protection associated with a future sea level rise will not be needed for a number of years. It might be best to take an adaptive management approach that incorporates actual rates of increase of threats, changes in the built and natural environment, and new technologies in an evolving protection scheme. However, this puts added demands on the current design, to enable future adaptions of the Ring Barrier, pump stations and the Seawall. Adaptability of all three components did not seem to be addressed much, if at all, in the Report.

There are other unanswered questions regarding the design approach. The elevation of the proposed Ring Barrier, 14 ft, is uniform along its entire length. Is uniformity in elevation an important design criterion, even though the overtopping threat varies around the periphery of the Ring Barrier? Is the 100-yr overtopping rate the design standard, or something else? Is the "ultimate limit" overtopping rate of 1 cfs/ft the standard, or is it a lower value? What is the ultimate limit value of overtopping for the inverted T-wall, that has a concrete pad on the land side to withstand overtopping and overflow, and how was it determined? Can the overtopping design standard be increased by extending or strengthening the scour pad, or by armoring the pad with stone riprap?

Clarification is needed for the overall design and implementation approach that is being recommended for both the Ring Barrier and Seawall improvements, and for the exact design standards that are being applied. The Feasibility Report states that additional work on designing the Ring Barrier will be done at the PED stage. We concur that there is much more work that needs to be done to find an acceptable solution for the City of Galveston that performs well for present and future sea levels.

Ring Barrier Composition and Elevation

We recommend a design approach that thoroughly incorporates city functions into the protection using urban landscape architecture best practices. Present plans call for a concrete floodwall (inverted T-wall) for most of the Ring Barrier perimeter. This solution can be visually unappealing, obtrusive and divisive in some areas such as the historic downtown area. In heavily industrialized areas, such as the Port, a plain concrete floodwall might be fine and unobtrusively integrate well into existing infrastructure. Walls certainly have a place, particularly where space is limited. In open less developed areas, natural-looking turf covered earthen/clay levees could be an attractive alternative. More work needs to be done to select the best solution for the area in which it is to be implemented.

Figure 5-3 shows the reaches that were considered in the analysis of wave overtopping, to aid in the design of the Ring Barrier and sizing of pumps. Representative 100-yr significant wave heights and water surface elevation (WSE) were calculated for each reach, then both were used to calculate overtopping rates and volumes for each reach.

Figure 5-3. Reaches consider in designing the Galveston Ring Barrier

Table 5-1 shows the calculated design WSEs and significant wave heights, for the different reaches shown in Figure 5-3. The 90% confidence limit (CL) values correspond to the adopted design standard. All design WSEs shown in Table 5-1 are for the present sea level. Table 5-2 shows calculated overtopping rates, 50% and 90% CL values, for the 100-yr wave and water level conditions, representing both present and future sea levels. Overtopping values in Table 5-2 utilized the WSEs and wave heights from Table 5-1, and a 2.1 ft increase in water level was used to represent the effects of rising sea level for the intermediate rise scenario.

Results in Table 5-1 show that, for present seal level, design WSEs appear to monotonically increase from east to west around the periphery of the Ring Barrier. The with-project 100-yr WSE is lowest, 10.3 ft, near the historic downtown area, increases to 11.3 ft in the industrial area to the west of the Port, to 11.8 ft at Offatts Bayou, and to a maximum of 12.3 ft along the western side of the Ring Barrier. The highest wave heights (6 to 7 ft) occur where the Ring Barrier is subjected to the largest waves that are generated in Galveston Bay, areas not protected by Pelican Island. Pelican Island affords sheltering and protection from wave energy to the UTMB campus area, historic downtown area, and the Port of Galveston. Design wave heights behind Pelican Island range from 2.4 to 3.9 ft. Due to the very limited fetch, wave periods must be quite small as well, so total wave energy in this area is relatively low. Design wave heights along the western side of the Ring Barrier range from 2.5 to 4.4 ft.

Table 5-1. Design water surface elevation (WSE) and significant wave height for the 100-yr year case and present sea level

Point	WSE [ft NAVD88] - 50% CI	WSE [ft NAVD88] - 90% CI	Hs [ft] - 50% CI	Hs [ft] - 90% CI
11892	10.0	12.3	2.1	2.5
12773	9.2	11.3	5.3	6.2
12841	8.6	10.6	2.0	2.4
12962	9.6	11.7	5.8	6.8
17276	8.3	10.3	3.3	3.9
17284	9.6	11.8	4.0	4.6

Table 5-2. Summary of overtopping rates [cfs/ft] for design wave and water level conditions, and present and future sea level

Point	100-year, 50% CI, 0.0' SLR [cfs/ft]	100-year, 90% CI, 0.0' SLR [cfs/ft]	100-year, 50% CI, 2.1' SLR [cfs/ft]	100-year, 90% CI, 2.1' SLR [cfs/ft]
11892	0.03	0.61	0.11	1.08
17284	0.30	1.76	0.58	2.98
12962	0.07	1.06	0.64	4.17
12773	0.003	0.19	0.18	1.86
12841	0.002	0.01	0.001	0.11
17276	0.05	0.39	0.03	0.90

In the USACE Plan, a uniform Ring Barrier elevation of 14 ft is proposed for the entire perimeter. The rationale for selecting a uniform elevation is unclear, in light of the variability of overtopping rates shown in Table 5-2. Overtopping rates near the historic downtown area are much smaller than rates calculated for the other reaches. For present sea level, rates in that area are a factor of 20 or more less than rates in other reaches; and for future sea level, a factor of 10 or more less than rates experienced elsewhere. This occurs because of the low WSE and low wave energy due to sheltering by Pelican Island. Overtopping rates suggest that a lower barrier elevation might be possible in the historic downtown area; a lower barrier there is certainly desirable. We recommend further investigation into the possibility that a lower barrier can be implemented in the historic downtown area. Beyond the sheltering effect of Pelican Island, where WSEs increase and wave energy increases greatly, overtopping rates are highest. It seems that a higher barrier or some other land-based measure can be implemented to reduce overtopping in this area to an acceptable amount. A higher wall in the industrial area west of the Port might be quite acceptable. Other possible methods for reducing the relatively high rates of overtopping in this area are discussed more in a later section.

The transition from the 14-ft Ring Barrier to the 21-ft Seawall at its western end will have to be closely examined and designed carefully. An abrupt transition in elevation should be avoided. The gradient of storm surge and wave conditions as surge levels decrease from the Gulf side to the bay side in this area should be considered in designing this transition. Missteps could lead to vulnerabilities and unanticipated leakage of storm surge into the Ring Barrier's interior. This area is likely to have high and turbulent flow directed toward the bay. The transition also might require armoring of the front side of the Ring Barrier.

Seawall Modifications

The USACE plans to raise the Galveston Seawall and incorporate measures to reduce the rate of overtopping into the raising. A 4ft additional vertical wall on the landward side of Seawall Blvd. has been proposed to raise the Seawall. This addition would be quite disruptive to businesses along the seawall. Alternatives could be attractive such as small berms. Also, the structural integrity of the Galveston Seawall in the (new) design condition has to be verified.

We concur with the plan to ensure that the Galveston Seawall has a uniform crest elevation over its length, eliminating any non-uniformities (vulnerabilities) that exist, which could serve as conduits for unanticipated overtopping and overflow into the City.

We recommend that the Seawall elevation be slightly higher (1 or 2 ft) than the top elevations of the adjacent land barrier and Bolivar Roads Surge Barrier, to help divert storm surge away from the City. This is not the case in the USACE Plan.

In the USACE Plan, design of pump stations assumes that overtopping of the Galveston Seawall is negligible. It appears that this assumption has not been demonstrated for the present sea level. The Feasibility Report indicates that if overtopping is non-negligible, then pump capacities will have to be increased. It will be important to design improvements to the Seawall such that overtopping is reduced to an amount that is consistent with assumptions made to size the pumps. We recommend laboratory scale modeling be done to aid the design of Seawall improvements. We also recommend that scale modeling be done to quantify how much overtopping occurs for hurricane events that exceed the design standard, which are used to assess resiliency of the entire system, such as a 500-yr overtopping event.

Some places in the Feasibility Report indicate that the Seawall raising is a "future adaption" but the main report says the seawall be one of the initial focusses for design and construction. Clarify when construction of the seawall raising is to begin. If planned for the future, what will trigger the construction? The current elevation of the Seawall is 17 ft, and the with-project 100-yr water level is 16.5 ft for present sea level (from Figure 2-22 in the Feasibility Report). The current seawall is quite vulnerable to substantial overtopping for the 100-yr design standard. If raising is to wait, it is of concern that sizing of the pump stations for present sea level assumes negligible overtopping of the Seawall.

Detached Breakwaters for Reducing Overtopping

As shown in Figure 5-1, detached breakwaters are being considered to reduce overtopping in the area just to the west of the Port, which is unprotected by Pelican Island and experiences the highest overtopping rates among all reaches. That seems like a rather expensive solution. If reduction in overtopping is the sole purpose, why isn't raising the height of the Ring Barrier in this area being considered, or if it was considered, why was it rejected?

There are other land-based options for dissipating wave energy and reducing overtopping that have a lower cost, such as …

- a different type of wall, like a recurved wall face to reduce overtopping
- a low rubble dike some distance in front of the inverted T-wall to trip and break the waves, such as elevating the bed of a rail line on a small rubble dike
- use of more natural features such as grass covered berms or dikes, perhaps in concert with dense vegetation. The Dutch use a technique of excavating soil to increase water storage capacity and using the excavated soil to construct a berm. Perhaps excavation could be done to enhance movement of water toward Offatts Bayou, with the material used to construct the berms. Or, bring in more erosion resistant clay to form an earthen dike or berm, compact it, then add top soil and grass cover like what is done in the Netherlands for levee construction, and was done in New Orleans. The wave action will not last very long so severe erosion potential is reduced, and the overtopping threat is addressed by the inverted T-wall
- A line of readily available precast concrete forms that are filled with sand or soil and capped with concrete, or perhaps covered with soil and vegetated

We recommend consideration and analysis of other alternatives to the detached breakwaters, and evaluation of their benefits, costs and acceptability to local stakeholders.

Armoring

Following the lessons of New Orleans, where walls are used, it is important to armour on the land side to withstand overflow/overtopping without breaching (a resilience requirement). All elements of the Ring Barrier need to be able to withstand the effects of overtopping and steady overflow, for the system to be resilient and remain robust when design conditions are exceeded. We recommend evaluating overtopping and overflow for a hurricane from the simulated set of storms that produces the highest overtopping conditions along the Ring Barrier periphery and the Seawall, and using these conditions to design scour protection for all elements of the Barrier, to ensure its resiliency.

Lessons learned from Hurricane Katrina also indicated that failures can occur where there are abrupt changes in elevation of walls/levees and at transitions between walls and levees. Failures at such locations generally occurred because of flow concentrations and/or overtopping and steady overflow that caused scour and subsequent breaching. Perhaps this a reason for the uniform elevation for the Ring Barrier in the USACE Plan. We expect that well-designed scour protection can be implemented at transitions involving small changes in barrier elevation, avoiding any potential scour problems.

Environmental Forcing (Surge, Rainfall and Sea level Rise)

The Galveston Ring Barrier needs to deal with coupled hazards, i.e. rainfall and surge during a hurricane. Over the long term, this is a difficult project to design and operate, with both major flood threats increasing – sea level and rainfall rates. Drainage and retention systems need to be designed to accommodate this. The co-occurrence (i.e. dependence) between rainfall and surge need to be further studied and characterized for inclusion in the design process. This also applies to the Clear Creek and Dickinson gate and pumping systems that are also affected by rainfall, runoff and surge simultaneously.

The updated H&H work examined the newly published NOAA precipitation rates, but they have not yet been included in the modeling. The 25-yr rainfall rates used previously (12.7 in) is approximately 10% higher than the new NOAA rate (11.5 in). How much do the 50-yr, 100-yr, and 500-yr rates used before differ from the new NOAA rates?

Interface with the Local Drainage System

The New Orleans' experience with rain-induced flooding inside their ring barrier teaches us that their city's drainage system cannot efficiently get the water to the ring, to be pumped over the barrier. The City of Galveston, like New Orleans, is responsible for its internal drainage. The City has active and planned drainage improvements. We are not convinced that these improvements have been adequately interfaced to the USACE Plan. It is not clear that all the areas within the proposed Ring Barrier will be able to drain efficiently to the ring boundary and reach the USACE-planned pumps. Proper interfacing is essential for the project to protect from rain-induced flooding.

The USACE Plan relies on considerable lengths of large buried enclosed channels/conduits for transporting water to the pump stations. Feasibility of this aspect of the Plan has not been demonstrated. In light of possible obstructions posed by utilities or other factors, the feasibility of constructing such channels should be evaluated.

Pump and Barrier Operations

The 100-yr design standard is not a particularly high one, far lower than that used in the Netherlands when they design ring barriers around concentrations of people. What back-up systems or redundancies are planned in the event pumps are overwhelmed or inoperable? It will be critical to make sure the gates leading to Offatt's Bayou can be operated during the widest possible range of head differences that can exist between interior and exterior water levels in order to dewater the ring interior.

When hurricanes approach the coast, they deposit a considerable volume of water onto the continental shelf. Once the eye moves through and winds subside, and the Bolivar Roads gates are reopened, the head difference between the Gulf and Bay water levels will force water to flow in the bays. This could raise levels inside the bays by several feet, changing tail water elevations. How might this process influence pump operations and a desire to reopen the gates leading to Offatt's Bayou? What about the pump stations at Dickinson and Clear Lake?

Most of the H&H modeling assumes a tail water elevation of MHW. However, seasonal steric effects, which vary from hurricane season to season, and within a season, and the surge forerunner that accompanies an approaching major hurricane might increase the water surface by up to several feet above MHW. How would such increases in tail water effect the design and operation of the pumps, and time required to pump down Offatt's Bayou? Same question for a higher future sea level.

Removable floodwalls are proposed. How long does it take to install and remove them, and what equipment/manpower is required? Where are they stored in relation to the deployment site(s)? What is the risk of encountering a problem with such a measure? It seems preferable to have something “in-place” that just has to be closed by swinging, dropping, or lifting. Suggest the USACE reevaluate the design if it cannot be operated in this manner.

Resiliency to Rising Sea level and Extreme Events

It is important that the Ring Barrier be resilient for rising sea level and for extreme hurricanes that exceed the design standard. The Ring Barrier should experience minimal damage and remain robust and operational for extreme hurricanes, including for another hurricane that occurs later during the same hurricane season.

Neither the 14-ft Ring Barrier nor the 21-ft Seawall appears to account for future sea level rise. To do so requires raising the elevation of the Ring Barrier by 4 ft; and, as yet undetermined, modifications to the Seawall and perhaps to the pump stations and other component that transport water to the pump stations. With rising sea level the City becomes increasingly more susceptible to greater amounts of overtopping and overflow.

What is the plan for evacuating water from within the Ring Barrier when the pump capacity is exceeded and possibly overwhelmed? Resilience in the face of increasing future sea level and extreme events that exceed the design standard should be assessed and planned for, and the plan clearly communicated, including an assessment of the residual risk. This topic should be addressed in the Feasibility Report.

Implications of a Stronger Coastal Spine

The City of Galveston would benefit greatly from a stronger coastal spine. JSU research suggests that a robust 17-ft Ike Dike would lower the 100-yr WSE along the bay side of Galveston by approximately 3 ft, compared to the USACE Plan. Wave conditions (significant height and energy) also will be reduced because of the reduction in surge levels. The reduction in 100-yr design water level and wave height will reduce the overtopping threat considerably. Consequently, we expect that for present sea level, a Ring Barrier elevation of 11 to 12 ft would meet the 100-yr design standard, compared to the 14 ft elevation in the USACE Plan. We expect that a Ring Barrier elevation of 13 to 14 ft would meet the 100-yr design standard for the intermediate future sea level rise scenario, instead of 18 ft in the USACE Plan. A significantly lower Ring Barrier elevation is a highly positive outcome, in light of stakeholder desires to minimize stick-up heights and make it the barrier less intrusive.

The lower elevation also will result in a significantly lower cost for the Ring Barrier or other flood protection schemes.

Chapter 6. Bay Defenses – Other Measures

Introduction

This chapter discusses the other in-bay measures for reducing flood risk and damage that are included in the USACE Plan, aside from the Galveston Ring Barrier (discussed in Chapter 5). In addition, other possible in-bay measures are identified and discussed. All equivalent average annual damage data cited in this chapter were extracted from Table 23 in Appendix E-1 of USACE (2020); data in Table 23 are for the intermediate sea level rise scenario and reflect damage to residential and commercial property. All damage data reflect average annual values computed for a 50-yr period of economic analysis. Cost data for in-bay measures included in the USACE Plan were extracted from the spreadsheets in Annex 22 to Appendix D of USACE (2020). In subsequent text, references are made to reaches that were considered in the USACE economic analyses. Economic reaches are numbered and are shown in Figure 6-1 (the figure is from Figure 2 in Appendix E-1).

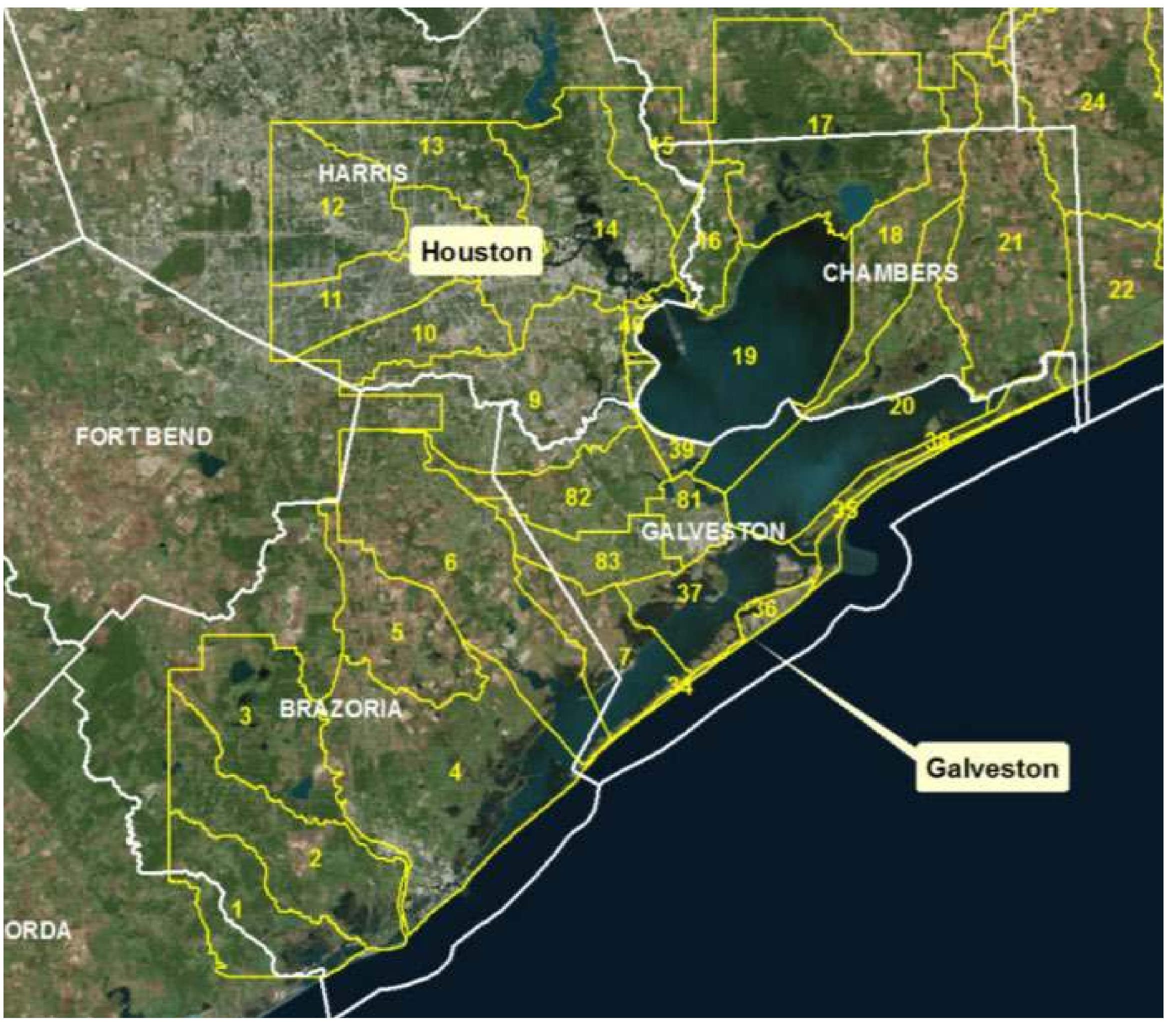

Figure 6-1. Economic analysis reaches considered in USACE (2020).

We concur with a multiple-lines-of-defense approach to reducing flood risk, which is reflected in the USACE Plan. The Plan includes: 1) a long continuous coastal spine situated at the coast, intended to produce the majority of flood risk reduction benefits for the region, 2) shorter, localized second lines of defense where there are strategic opportunities to reduce residual risk further in higher density urban or industrial areas, and 3) non-structural measures implemented at the scale of individual residential and commercial properties in less densely populated and industrialized areas. However, as discussed in previous chapters, the weak land barrier included in the USACE Plan, and omission of a western section of the coastal spine that includes a gate at San Luis Pass and land barrier on Follets Island, allows considerable storm surge to enter both bays. Consequently, the USACE Plan has very high residual damage associated with it. For the intermediate future sea level rise scenario, there are \$2.85B of average annual damages for the without-project condition, an average annual damage reduction of \$1.70B, and a very high average annual residual damage of \$1.15B.

It is unclear what rationale was adopted by USACE for selecting certain areas to receive second lines of defense and nonstructural methods, and not others. Without a clear rationale, choices appear to be arbitrary and illogical, particularly in light of the magnitude and wide distribution of residual damage throughout both bays. The current USACE Plan for in-bay measures appears to only focus on certain areas of Galveston Bay, despite the split in residual damages between Galveston (45%) and West (55%) Bay, with more damage in West Bay. Second lines of defense, short wall/gate systems, are proposed at Clear Lake and Dickinson, but not in other areas with high residual damage. Non-structural methods are only proposed for the western side of Galveston Bay and in a single community adjacent to the Galveston Ring Barrier, and not in other areas where residual damage is even higher.

Because of the very high residual damage associated with the USACE Plan, the need for and desirability of in-bay measures increases along with the likelihood that many measures are cost-effective, more than have been proposed by the USACE. We believe there are other opportunities around the periphery of both Galveston and West Bays to reduce residual risk further. We recommend careful consideration, with analysis of benefits and costs, of potential second-lines-of-defense and non-structural measures in other areas throughout the region. Is does not appear that such a region-wide analysis was done.

Wall/Gate Systems at Dickinson and Clear Lake

Short wall/gate systems are included in the USACE Plan for the entrance channels that lead to both the Clear Lake and Dickinson areas (economic Reaches 9 and 82 in Figure 6-1, respectively). Both second-lines-of-defense take advantage of strategic opportunities to reduce storm surge propagation into a densely populated flood plain by placing a wall/gate system across the conveyance channel that leads to the flood plain. Once closed, the gate system reduces penetration of the storm surge, much like the functionality achieved with the Bolivar Roads gate system, which significantly suppresses surge penetration into Galveston Bay.

We recommend an extensive and detailed examination to identify other possible strategic locations around the periphery of Galveston and West Bay that also might be conducive for a second line of defense. Possible measures include a similar wall gate system, and/or a levee, or other temporary flood defense system that might reduce residual flood risk for industrial or port facilities, or more densely populated communities, further.

The Clear Lake wall/gate system has a first cost of $1.52B and fully funded cost of $2.77B. It helps reduce average annual damages in economic Reach 9 from $558M (without project) to $111M (with project), a benefit of $447M. It appears that significant benefits accrue because of this wall/gate system; although there is insufficient information to isolate its benefits relative to those achieved with the coastal spine, the first line of defense. The Dickinson wall/gate system has a first cost of $ 880M and fully funded cost of $1.65 B. It helps reduce annual average damages in Economic Reach 82 from $155M to $14M, a benefit of $141M. Fewer benefits accrue with the Dickinson wall/gate system compared to the Clear Lake system, but the cost is less.

As a cost-effectiveness metric, an indicative Benefit/Cost ratio (BCR) is defined, where:

> Benefit = the reduction in average annual damage produced by some protective measure, multiplied by 50 yrs to reflect a 50-yr period of analysis
>
> Cost = fully-funded cost of the protective measure over a 50-yr period of analysis

The larger the BCR for a given protective measure, the more cost-effective it is.

For the Clear Lake wall/gate system, the BCR is (0.447B x 50)/2.77B, or **8.07**. For the Dickinson wall/gate system, the BCR is (0.141B x 50)/1.65B, or **4.27**, roughly half as cost effective as the Clear Lake system but still quite favorable. Despite the fact that some, perhaps much, of the damage reduction in both areas is realized because of the coastal spine, the BCR is a reasonable metric for comparing different in-bay measures. All in-bay measures benefit from the coastal spine.

It does not appear that flanking of either short gate/wall system by the storm surge was considered in its design. Based on 2008 LIDAR data, it appears as though terrain elevations adjacent to both gates (8 to 10 ft) are significantly lower than the still water level used to design them (<u>12.8</u> ft at Dickinson Bay and <u>13.5</u> ft at Clear Lake), and the low terrain extends for considerable distances. While high, the wall/gates at both locations are relatively short in length compared to the expanse of terrain that has elevations less than 10 ft. In light of their relatively short length (1.5 miles at Clear Lake and 0.7 miles at Dickinson), and their apparent susceptibility to flanking by a storm surge that is even less than the 1% AEP SWL, we recommend further investigation into the optimal length and height for both of these wall/gate systems. The issue of length for both systems is discussed in Chapter 12 of the Jackson State University, JSU (2018) report. In addition, it does not appear that flanking of the Dickinson and Clear Lake wall/gate was considered in sizing of the pumps. If not, we recommend this investigation be done as well.

Another Pathway for Storm Surge to Enter Clear Lake

Surge model results presented in USACE (2020), and JSU (2018) surge modeling, reveals an apparent overland pathway by which Galveston Bay internal surge can propagate over low-lying terrain and enter the northeast side of the Clear Lake area. This pathway is located near the Shoreacres community. This is a different pathway than that addressed by the proposed wall/gate system at Clear Lake. This pathway appears to be a significant contributor to the high residual damage that remains in the Clear Creek area (Reach 9) even with the second line of defense at the entrance to Clear Lake. The presence of such a vulnerability, and measures to eliminate or reduce the flooding impacts of this pathway, should be carefully investigated. This pathway is described and graphically illustrated in Chapter 12 of the JSU (2018) report.

Non-Structural Measures in the USACE Plan

In the USACE Plan, non-structural improvements are proposed for economic Reaches 39 and 40 on the western side of Galveston Bay, and in a small community in the City of Galveston that is left outside the proposed Ring Barrier. The first cost for these measures is $220M, with a fully funded cost of $420M. The total benefits of the nonstructural measures, in terms of reduced damage, are $38M ($3M in Reach 37, $30M in Reach 39 and $5M in Reach 40). For the full set of nonstructural improvements in the USACE Plan, the BCR is (38M x 50)/420M, or **4.52**, which is comparable to BCR for the Dickinson wall/gate system.

Consideration of Other Areas for in-Bay Measures

In light of the very high residual damage associated with the USACE Plan and its wide spatial distribution, we recommend consideration of, and analysis of, costs and benefits associated with second lines of defense and/or nonstructural methods for other areas around the periphery of both West and Galveston Bays. A focus for other possible second lines of defense should be urban, port and industrial areas where residual damages are highest and/or are concentrated. A focus for non-structural methods should be on these same areas, as well as more sparsely populated areas.

Examination of residual damage in the different economic reaches shown in Figure 6-1 suggests other areas where implementing second lines of defense or non-structural methods might be cost effective. In Table 6-1, the rank-ordered list shows average annual residual damage by economic reach. Only those reaches with average annual residual damage in excess of $10M are shown in the table. There are other areas around the north and east sides of Galveston Bay have smaller levels of residual damage, and are not listed in Table 6-1. These areas also might be candidates for non-structural methods that can be implemented on a property-by-property basis. We recommend this possibility be explored for these areas as well.

In West Bay, two economic reaches, 37 and 4, comprise the bulk of the residual damage. The residual damage in both of these reaches is roughly twice as much as residual damage in any other reach in either West Bay or Galveston Bay. These two reaches should be closely examined to identify the opportunities and potential for cost-effective in-bay measures. Chapter 12 of the JSU (2018) report explored the footprint of some possible second lines of defense (levees, or levees with gates) for Reach 37, which is situated along the easternmost portion of the north shore of West Bay, adjacent to the western portion of the Texas City Levee.

Table 6-1. Residual equivalent average annual damages by economic reach for Galveston and West Bays

Economic Reach	Average Annual Residual Damage	Reach Location – by Bay
Reach 37	$217 M (*214 M)	West Bay (the USACE Plan induces $51 M)
Reach 4	$212 M	West Bay
Reach 9	$111 M	Galveston Bay
Reach 81	$101 M	West Bay
Reach 14	$60 M	Galveston Bay
Reach 39	$60 M (*30 M)	Galveston Bay
Reach 7	$41 M	West Bay
Reach 38	$29 M	Galveston Bay (the USACE Plan induces $11 M)
Reach 83	$28 M	West Bay
Reach 6	$19 M	West Bay
Reach 82	$14 M	Galveston Bay
Reach 34	$13 M	West Bay
Reach 13	$13 M	Galveston Bay
Reach 40	$12 M (*5 M)	Galveston Bay

*These values indicate residual damages associated with implementation of non-structural methods

The USACE Plan actually induces damages in a two reaches, compared to without-project damages; and those areas are indicated in Table 6-1 with underlined text. The USACE Plan induces $51M in average annual damage in reach 37. This is a significant amount. With the exception of one small neighborhood in the City of Galveston, there are no other measures proposed to mitigate the more substantial induced damage throughout this economic reach. The same is true for Reach 38, on the eastern half of Bolivar Peninsula, where the USACE Plan also induces $11M in average annual damage. We recommend consideration of mitigation in these areas where the USACE project induces damage. Mitigation might include structural or non-structural in-bay measures and/or nature-based solutions to reduce wave-induced damage.

Significant residual average annual damages remain in the Texas City economic reach, Reach 81 ($101M). JSU research, see Chapter 12 of the JSU (2018) report, indicates that the southwest termination point of the Texas City Levee can be flanked by severe surge-producing events. This appears to be the source of the residual damage. Model results presented in USACE (2020) also show evidence of this flanking for severe hurricanes. For the weak land barrier included in the USACE Plan, this area is a candidate for a second line of defense. The cost and benefits of an in-bay measure here should be explored, probably via a modification/extension of the Texas City levee at its southwestern terminus. As demonstrated in Chapter 12 of the JSU (2018) report, a robust 17-ft Ike Dike eliminated this flanking even for the 500-yr proxy storm and future sea level rise of +2.4 ft. We expect that a robust 17-ft Ike Dike will completely eliminate this significant residual damage, or nearly so.

Surge modeling by JSU and the USACE both suggest that Reach 14, surrounding the upper Houston ship Channel, will have the highest residual 1% AEP SWLs in all of Galveston Bay, due to in-bay surge generation. Chapter 12 of the JSU (2018) report shows, in a revealing visual way, those industrial areas in Reach 14 that are most vulnerable to residual flooding and damage. We recommend that these industrial areas, and any others in those areas with high residual risk, such as in Reach 4, be examined and evaluated as candidates to receive a second line of defense. Several such areas in Region 4 were identified in Chapter 4.

The listing in Table 6-1 also shows the degree to which non-structural measures reduced residual damage, in those few areas where they are proposed as part of the USACE Plan. The residual damage that remains even with implementation of nonstructural measures is indicated with an asterisk in the table.

The rationale, analysis and evaluation that lead to the selection of economic Reaches 39 and 40 for widespread non-structural measures, and no other areas, is unclear. Residual damages in a number of reaches exceed those in Reach 39, by considerable amounts in some reaches; and all other reaches shown in Table 6-1 exceed the residual damages for Reach 40. Collectively, the reaches around West Bay contain many more structures than those in reaches 39 and 40. Since non-structural measures seem to be implementable on an individual structure by structure basis (raising elevation or flood proofing), it is unclear why other areas around the periphery of West and Galveston Bays are not slated for such measures. We recommend that a system-wide investigation be done, encompassing the entire periphery of both bays, to assess the costs and benefits of implementing non-structural measures throughout the entire region. This is particularly important in light of the poor overall performance of the USACE Plan and the very high residual risk that remains with the Plan.

Relationship between the Coastal Spine and In-Bay Measures

Every contribution to water height in Galveston and West Bays increases the surge in the bays and the need for and height/strength of every single in-bay second line of defense and non-structural measure. For the USACE Plan, the weak land barrier and the absence of a western section to the coastal spine including a gate at San Luis Pass (see Appendix A) lead to significant storm surge entry into both bays, increasing the need for in-bay measures. The size and cost of all in-bay measures is inversely related to the strength of the coastal spine. Improving the coastal spine would help lower water levels everywhere in the bays and should be a priority. A robust 17-ft Ike Dike lowers the 1% SWLs in the bays by 3 to 6 ft, compared to the USACE Plan. With the 17-ft Ike Dike, the elevation and costs for all in-bay measures will be reduced significantly. We expect that many in-bay measures that are cost-effective with the USACE Plan will not be needed with a robust 17-ft Ike Dike.

Nature-Based Solutions

Wherever terrain gradients are lowest, on the bay sides of the barrier islands and other locations around the peripheries of the bays, these areas are highly susceptible to flooding, sensitive to small changes in surge levels, and to rising sea level. Nature-based solutions provide a means for reducing damage caused by storm surge and waves. Even where nature-based solutions cannot significantly reduce storm surge levels, they can reduce wave energy, which can lead to a reduction in wave-induced damage and overtopping. A study by Godfroy et al. (2019) has shown that marshes on the bay side of Galveston Island can lead to a 60% reduction in significant wave heights in 100-year conditions. Nature-based features can reduce wave energy and overtopping potential, leading to reduction in required elevation for more hardened second lines of defense and nonstructural measures.

As part of the ecosystem restoration intervention G28 (Bolivar and West Bay GIWW shoreline and island protection – east) a total of 40 miles of rock breakwater is proposed (section 3.2.1 of the USACE (2020) main report). We recommend an investigation to assess whether or not nature-based features, which will also provide coastline protection and environmental value, can replace portions of these breakwaters, without and with improvements to the USCE coastal spine discussed in previous chapters.

Marshes or other nature-based measures can mitigate, at least partially, for damage induced by the USACE Plan in economic reaches 37 and 38. As part of intervention G28, considerable marsh building is planned along the bay side of Bolivar Peninsula. We recommend investigating the enhancement of the marsh restoration in Reach 38, through additional marsh creation or implementation of other nature-based measures to mitigate for the induced damage in this reach, perhaps in conjunction with second lines of defense or nonstructural measures.

Leaving the "back door" open to surge penetration, by not including a western section to the coastal spine, leads to considerable residual storm surge and wave damage around the periphery of West Bay (see Chapter 4). In addition to consideration of implementing second lines of defense or nonstructural measures to address the high residual damages around West Bay, we recommend investigating use of nature-based measures to reduce damage to communities on western Galveston Island (those outside the Ring Barrier), as well as communities and industrial facilities along the north shore of West Bay.

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Chapter 7. Bolivar Roads Storm Surge Barrier

General findings

This chapter focuses on the Bolivar Roads storm surge barrier. The study of the barrier is comprehensive and state-of-the-art, and it is very complete in the sense that it covers a lot of aspects (technical, environmental, financial, planning). The way of online presentation and visualization of the barrier and features is innovative, and it makes the planning efforts insightful and accessible for a broad audience.

The study is clearly rooted in linked to previous studies by USACE, GLO, TAMUG / TU Delft and others, also utilizes international experience from the international I-Storm network. The constriction of the proposed storm surge barrier (7-10%) is very small compared to other barriers around the world thus leading on relatively limited effects on tidal range and flows in Galveston Bay. Based on this it would be expected that the effects on environment in Galveston Bay are minimized. This is supported by comprehensive environmental flow modelling.

Yet, there are a number of issues that need to be considered in further design and planning of the barrier:

1. The reported cost estimate of the Bolivar Roads barrier is 13.8 B$. This seems (very) high. A cost estimate of the same barrier design has been made using a recently developed method which is based on the costs of existing barriers around the world, and the dimensions of the various barrier features. This leads to a cost estimate of 4.6 B$ (bandwidth 2.4 B$ - 6.8 B$). It is recommended to (re)consider the cost estimate and optimize the design (see below).
2. The proposed floating sector gate is vulnerable for back surge. It is recommended to consider alternatives, such as a barge gate.
3. In the current plan two main navigation channels with navigational gates (each 650 ft wide) are proposed. One channel with reliable gates is expected to be reliable and sufficient for navigation. This solution will also contribute to lower costs.
4. It is required to further address longer term management, funding and maintenance of the surge barrier system (and other system features).

These topics are further elaborated in the following paragraphs. In this report reference is made to the engineering appendix of the USACE / GLO report (USACE, 2020), unless stated otherwise.

Cost estimate

The reported cost estimate of the Bolivar Roads barrier is 13.8 B$ in project first costs (FY2019)[1]. This seems very high when compared with cost estimates obtained with other methods. A cost estimate of the same barrier design has been made, using a recently developed method (Kluijver et al. 2019) which was developed in collaboration with the NY District of USACE and used for cost estimates for barriers in the New York – New Jersey harbour and tributaries study (USACE, 2019). The model is based on the costs of existing barriers around the world, and the dimensions of the

[1] Appendix D, Annex 22, p.2

various barrier features. It utilizes the following formula:

$$Cost = €157,000 \times Navigable\ Area + €102,000 \times Auxiliary\ Area + €26,000 \times Dam\ Area$$

Auxiliary area refers to the environmental gates; all areas in m^2; price levels in 2019 Euros. The exchange rate at this moment is € 1 = $ 1.20 and this value has been assumed here.

Note: The above formula does include planning, engineering and design costs. One difference with the USACE method might be that the above formula produces an expected (50%) cost value and also has values of the three unit cost constants for the 90% confidence interval[2]. The method by USACE includes contingencies which adds a margin of 28% to the estimated cost (appendix D; Annex 22_. It is not clear at this moment whether this contingency refers to a "variation from the mean" or some other metric.

Comparison of cost estimates

Application of the above method with the proposed barrier dimensions leads to a cost estimate of 4.6 B$ (and a bandwidth between 2.4 B$ and 6.8 B$). The distribution of the costs over various barrier features is shown in table 7-1 below.

Table 7-1. Cost estimate of the Bolivar Roads storm surge barrier as proposed by USACE, using the recent cost estimation method from Kluijver et al (2019)

Section	**Amount of gates**	**Width per gate (ft)**	**Avg. height (ft)**	**Total costs (M$)**
Combi wall	1	5300	20	338
Environmental gate shallow	16	96	26.5	463
Environmental gate large 20ft	8	300	30	819
Environmental gate large 40ft	7	300	50	1195
Navigational gate - large	2	650	70	1594
Navigational gate - small	2	125	50	219
Total				4627

Also a simpler rule of thumb has been used. From the analysis of previous barrier projects around the world it is found that the costs per meter width of opening are 2.96 M$/m (=2.47 M€/m) (Mooyaart and Jonkman, 2017; Kluijver et al., 2019). Application of this more simple rule of thumb leads to an expected costs of 6.8 B$ (and a bandwidth between 2.8 B$ and 11.1 B$). The more recent and advanced method gives a lower estimate (4.6 B$), as the gates for Bolivar Roads are relatively small and shallow. As a reference, costs of some other barriers are included in the table below.

[2] This equation corresponds with the mean. A 90% confidence interval can be defined based upon the dataset analyzed with the following slope intervals: +/- €60,000 on the Navigational area (NA) term coefficient, +/- €54,000 on the Auxiliary flow area (AA) term coefficient and +/- €13,500 on the Dam or static term (DA) term coefficient (Kluijver et al 2019).

Table 7-2. Properties and costs (2019 M$'s) of selected barriers[3]

	Barrier properties – width of various sections (m)			
Barrier	**Navigation gates**	**Environmental gates**	**Dam length**	**Cost (M$)**
Maeslant	360	-	-	972
New Orleans IHNC	220	-	2600	1580
Eastern Scheldt	-	2790	5074	5800
Bolivar Roads	473	1840	1616	USACE: 13882 Our estimate: 4627

It is recommended to (re)consider the costs of the storm surge barrier, and compare various cost estimation methods. It is noted that cost estimates are uncertain as these are unique projects, and costs will be much dependent on the exact design, market circumstances, material prices etc.

Gate selection: Floating sector or barge gate?

In the current plan floating sector gates have been chosen for the navigational channels. This gate solution has been used in the Maeslant barrier in the Netherlands (see Figure 7-3). This type of gate is vulnerable for "back surge" (higher water level on the back side: here Galveston Bay than on the Gulf of Mexico). This situation can occur due to the rapidly rotating wind fields associated with hurricanes. Figure 2-34 in the engineering appendix (copied below as Figure 7-1) shows that negative heads occur in many of the 170 sampled storms. Cases with a negative value on the vertical axis are associated with negative head

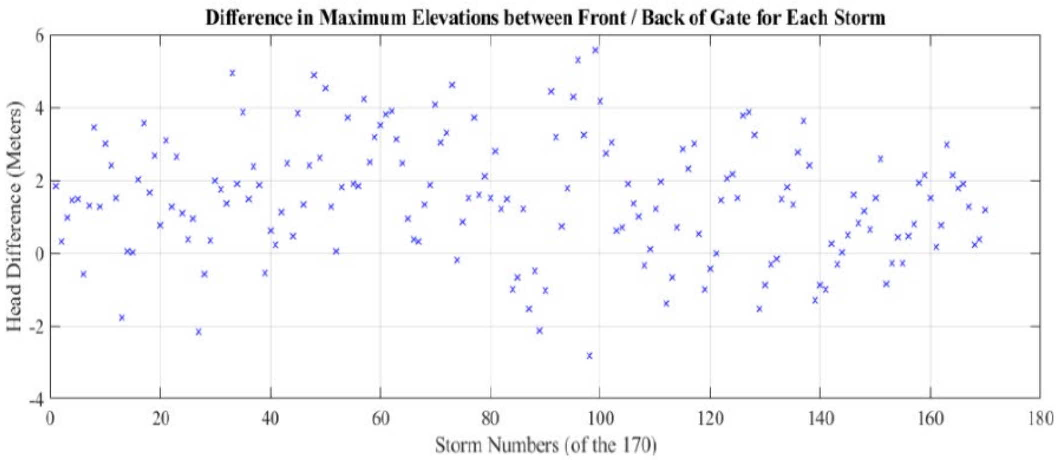

Figure 7-1. Figure 2-34 from the engineering report: Difference in elevations between front and back side of surge barrier (USACE, 2020)

[3] Source: dataset published as: Kluijver, Maarten; Dols, C. (Chris); Jonkman, Sebastiaan N.; Mooyaart, L.F. (Leslie) (2019): Dataset in support of Advances in the Planning and Conceptual Design of Storm Surge Barriers. 4TU.ResearchData. Dataset. https://doi.org/10.4121/uuid:9820d43f-9e20-48a6-a791-59e634fab30e

In case of back surge the sector gates could be “pushed out” of their hinges. The ball joint hinge is strong for pressure, but less strong for tensile forces associated with back surge.

Therefore the barge gate was selected as a preferred concept in previous design studies for the coastal spine concept (Jonkman et al., 2015) – see Figure 7-2. Such a gate could “self-open” (or at least be more easily controlled) in case of a back surge.

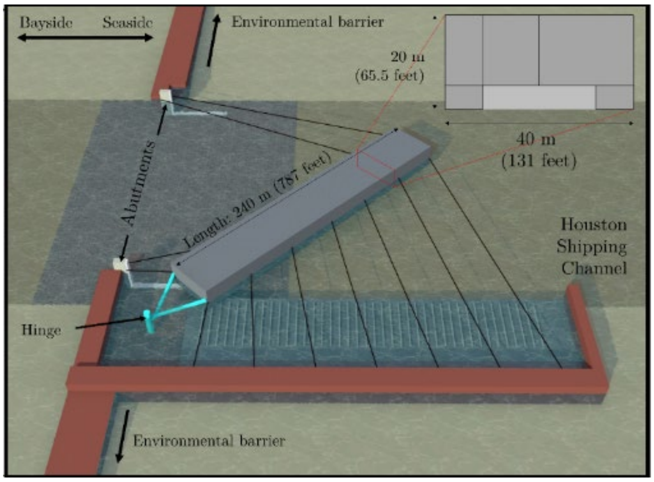

Figure 7-2. Conceptual design drawing of a floating barge gate designed for Bolivar Roads storm surge barrier (Smulders, 2015; Jonkman et al.). A structural design has been made in S355 steel for an opening of 787 ft. The weight of the barrier would be around 32,000 tons.

Other topics related to the barrier design

- Gate operation and closure frequencies:
    - It is stated on the project website that barriers will not likely be closed for a 50 year storm[4]. This is surprising as it is expected that a barrier (in combination with a good dune system) could prevent a lot of surge and damage for more frequent hurricanes (anywhere in the 5 – 50 years return period range). As a comparison, the Maeslant barrier in the Netherlands is expected to close every 5 to 10 years and the Eastern Scheldt barrier on an annual basis.
    - No further gate closure levels or frequencies have been given yet (section 9.5). This is an important aspect for operation, navigation and ports. It is recommended to give an indication by considering the expected number of hurricanes that lead to storm surge in the Galveston Bay area and gate closure. In that respect it could be useful in section 9.5 to mention to closure frequencies for the reported international barriers as well, not only closure water levels.
    - As introduced in chapter 2 of this report, it will be critically important to keep the hurricane surge including the forerunner out of the bay. The closure procedure should be optimized to achieve this.
- Scour protection (Section 6.7) my need further attention as it is also an important cost driver. This is important as very high flow velocities (~10 m/s) can occur below the floating sector gates, and when lift gates fail to close. So robust scour protection may be needed to withstand such flows and to avoid failure of support structures. Scour protection is an important cost driver.

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[4] https://storymaps.arcgis.com/stories/14c41d68d8984b129edb4c133b719de3; explanation next to 50 year storm.

One or two main channels?

In the current plan 2 main navigational channels (650 ft wide) with an island in the middle have been proposed. This creates an island between the two channels thus increasing likelihood of ship groundings and collisions. Choosing for two large gates also increases the costs significantly. The main arguments for this solution focus on the added redundancy and reducing the risk of not opening after a storm (page 6-16 & 9-7).

The current width of the navigation channel is about 800 ft and required width would be about 656 ft (table 6-7). It is recommend to explore if a solution with a single large navigational barrier for the main channel would be feasible. This would also contribute to considerable cost savings.

The choice for a barge gate will reduce the risk of not opening. Also, maintenance of gates can be done in dry docks if needed. It is noted that a one barrier solution has been chosen for the Maeslant barrier which has a total channel width of about 360m (1080 ft) – Figure. 7-3.

Figure 7-3. Maeslant storm surge barrier in the Netherlands - Width: 360m (1180 ft); Depth: 17m (56ft)

Longer term management, maintenance and funding of the Bolivar Roads storm surge barrier system

It is positive that attention has been paid to OMRR&R (chapter 9). Particularly the management, maintenance and operation of storm surge barriers is important and complex. These roles still need to be assigned.

The design life of a movable barrier is generally 100 years. During this long period of time, it is important to keep the barrier in good condition in such a way that it meets the requirements, in particular the required safety level, at an acceptable cost. Besides aging of the civil structure, the mechanical parts and the electrical systems, the relatively short life cycle of software and the relatively short memory of the O&M organization form major challenges. Account should also be taken of changing circumstances during the lifetime of the barrier, including environmental changes (i.e. changing intensity of hurricanes, sea level rise) and other developments (e.g. changes in available funding and organization). This makes the O&M of a movable flood barrier a complex task, which requires a careful and object-specific approach.

Barriers in the Netherlands have been designed in a risk-based way. This implies that the barrier is designed for a certain reliability level. Also, O&M is risk-based, i.e. maintenance investments, frequencies and strategies (failure-based, time-based or condition-based maintenance) are set up in such a way that risks are minimized. It is challenging to keep a well-equipped O&M organization as the number of actual storm closures is rare.

Experiences from other barrier and flood protection systems (New Orleans, Netherlands and other locations) can be utilized to develop the management schemes. It is also important to secure and plan longer term funding streams for management and maintenance. From experience with previous barriers, it is expected that annual maintenance costs could be up to 0.5% of the construction costs.

Overall, management and maintenance of a storm surge barrier requires considerable expertise, and guaranteed funding. Given the above factors (need for expertise, longer term funding, national and international exchange), USACE seems most suited to manage storm surge barriers.

Also, the maintenance of the dune system is important, as a lot of maintenance dredging will be needed to account for coastal erosion in regular conditions and during storms. Furthermore, operation and management of the Galveston ring system will be a challenging task as it includes a lot of moveable gates, pumps etc. It would be good to define the responsible authority.

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Appendix A. Dune Response Modeling

Introduction

In this appendix CSHORE (Johnson et al., 2012; Kobayashi 2013) numerical modeling results of beach and dune profile evolution under various hydrodynamic forcing conditions are presented. Table A-1 gives an overview of the presented cases. Many more combinations of dune geometry, core structure geometry and type, and storm impact scenarios have been simulated. The cases presented here are intended to give the reader a better feel for the land barrier profile response to storm impacts but are by no means an exhaustive compilation of all possible scenarios. The presented CSHORE results have to be understood as a first approximation only.

Table A-1. Dune response modeling results presented in this Appendix

Dune Design	Hydrodynamic Forcing	Core-Enhancement
Single 14 ft	10-year return value proxy storm	No core
Single 17 ft	Hurricane Ike (30-year return value)	Single core
Dual 12/14 ft	10-year return value proxy storm	No core
Dual 12/14 ft	Hurricane Ike	Dual core
Dual 15/17 ft	10-year return value proxy storm and Hurricane Ike	No core
Dual 15/17 ft	Hurricane Ike	Dual core
Dual 12/14 ft with widened crest widths	Hurricane Ike	Single seaward core
Dual 15/17 ft with widened crest widths	Hurricane Ike and 100-year return value proxy storm (with and without 2.1-ft sea level increase)	No core, single seaward core, single landward core

All core-enhancements are simulated as sloping solid impermeable structures 1 m below the sand cover surface for this assessment.

CSHORE Overview

The brief CSHORE overview here has been adapted from Harter and Figlus (2017). CSHORE is a very efficient process-based 1D cross-shore coastal response model. The model includes a time-averaged and depth-averaged combined wave and cross-shore current model, a time-averaged sediment transport model, a probabilistic model for the intermittently wet and dry zone, as well as empirical formulas for irregular wave runup. The model employs a linear wave theory based model with an assumed Gaussian distribution of the free-surface elevation below mean sea level (MSL) and a model based on the time-averaged continuity and momentum equations derived from nonlinear shallow-water equations above still water level (SWL) to provide hydrodynamic forcing for sediment transport and morphology changes. Outputs from both models are averaged in the zone between SWL and MSL to provide smooth results over the entire computation domain. The actual location of SWL and MSL at each time step dictates where along the profile the two models are applied. CSHORE predicts cross-shore variations of the mean and standard deviation of the free surface elevation, the depth-averaged cross-shore current, the cross-shore velocity standard deviation, the cross-shore bed-load transport rate, and the cross-shore suspended sediment transport rate. The root-mean-square wave height, spectral peak period and setup/setdown with respect to SWL are used as input at the offshore boundary of the computation domain. Only the initial bottom profile elevation is specified for the computation of the entire model run. Since CSHORE is a 1D cross-shore time-averaged model, it is most effective when applied to representative shore locations where bathymetric contours are approximately parallel. Computational efficiency, robustness, and relatively good accuracy are some of the major advantages of using CSHORE as a tool to predict beach profile changes. CSHORE parameter values used in this study follow Harter and Figlus (2017).

Hydrodynamic Forcing Conditions

The hydrodynamic forcing conditions used for most model simulations are adapted from Ebersole et al. (2018). Locations of data output from their modeling efforts are shown in Figure A-1. Since shown CSHORE model tests were mainly based on Galveston Island profiles, Stations 11 and 17 are used primarily. The time series of hydrodynamic forcing conditions at Stations 11 and 17 are shown in Figures A-2 and A-3, respectively. Parameters include water level, root-mean-square wave height, peak wave period, and mean wave angle of approach relative to shore normal.

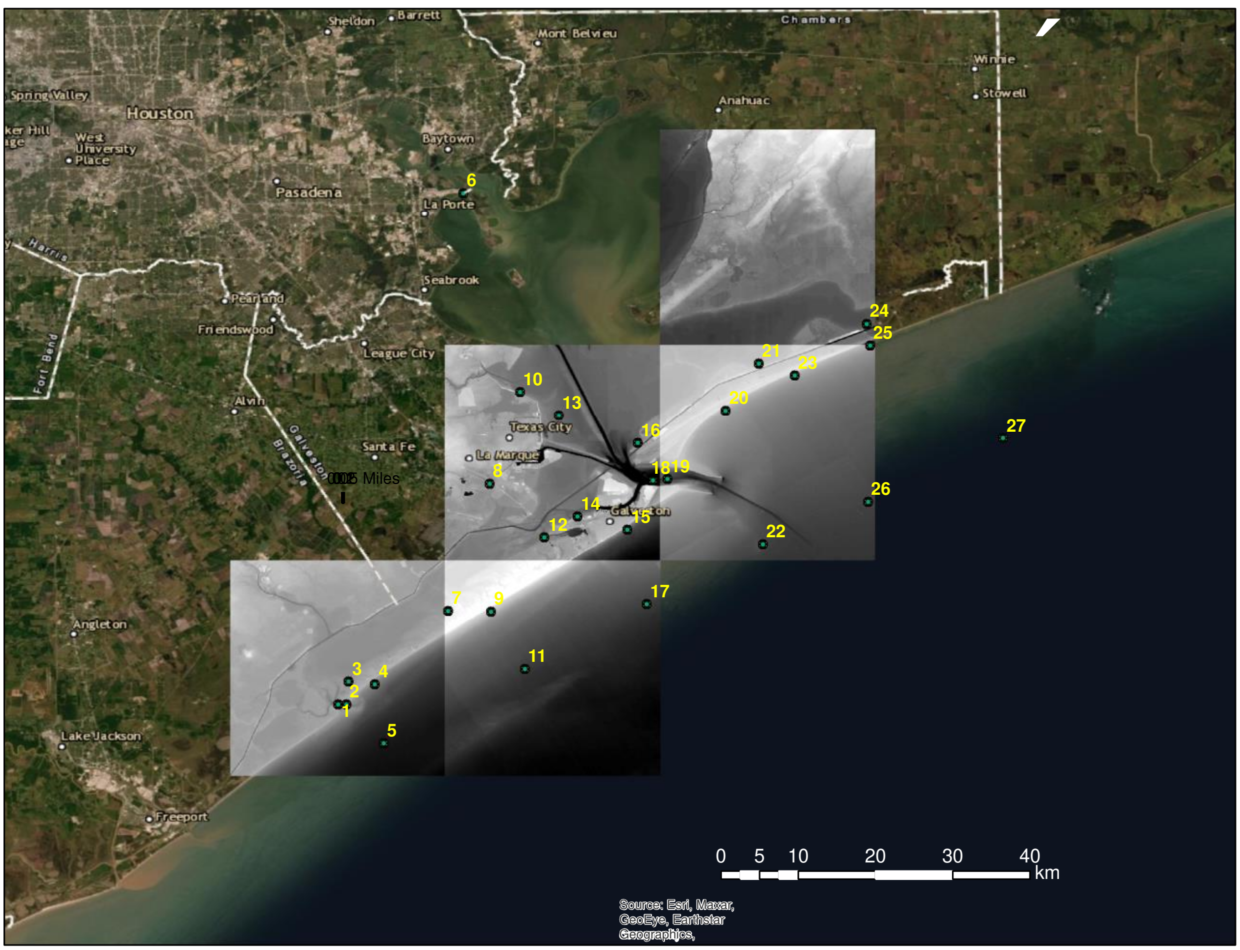

Figure A-1. ADCIRC output station numbers (Ebersole et al., 2018)

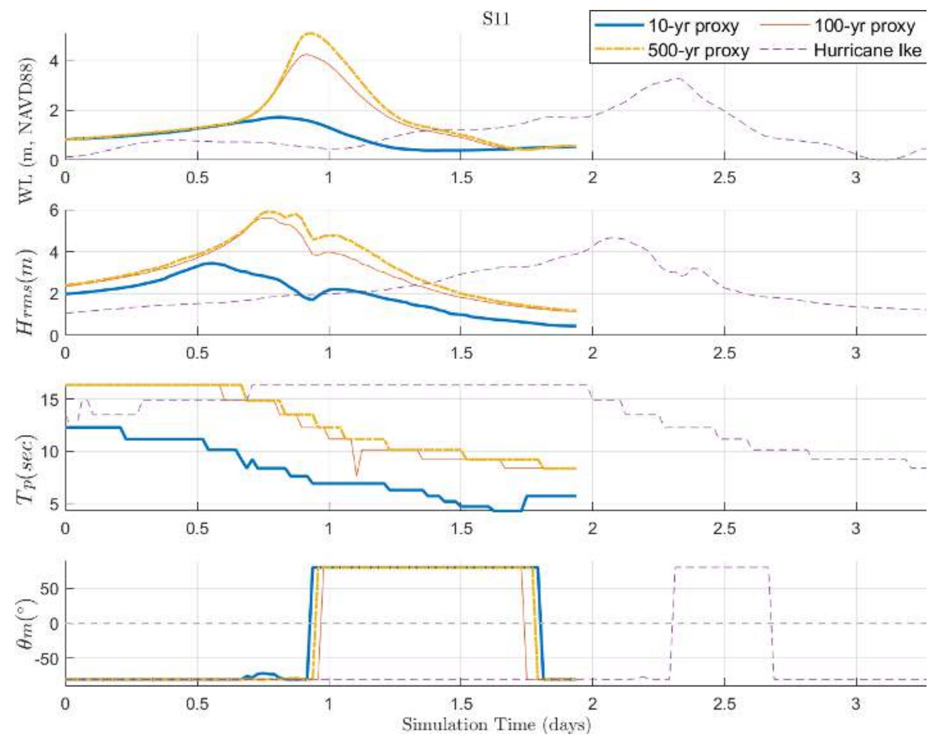

Figure A-2. Hydrodynamic forcing conditions used as CSHORE input. The time series are based on Ebersole et al. (2018) and are associated with location S11 (Figure A-1) at a water depth of 14 m.

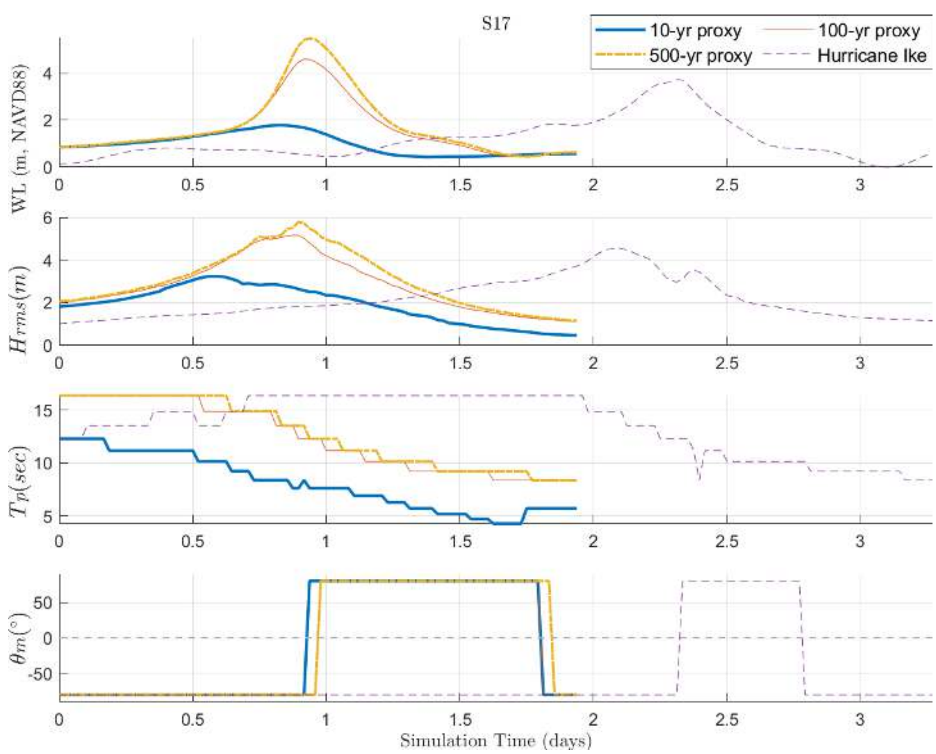

Figure A-3. Hydrodynamic forcing conditions used as CSHORE input. The time series are based on Ebersole et al. (2018) and are associated with location S17 (Figure A-1) at a water depth of 14 m.

Some CSHORE model simulations using hydrodynamic forcing conditions based on NOAA NDBC buoy 42035 measurements during Hurricane Ike (17 m water depth) were run as well since these have been used by the USACE for some of their SBEACH modeling (see Figure A-4).

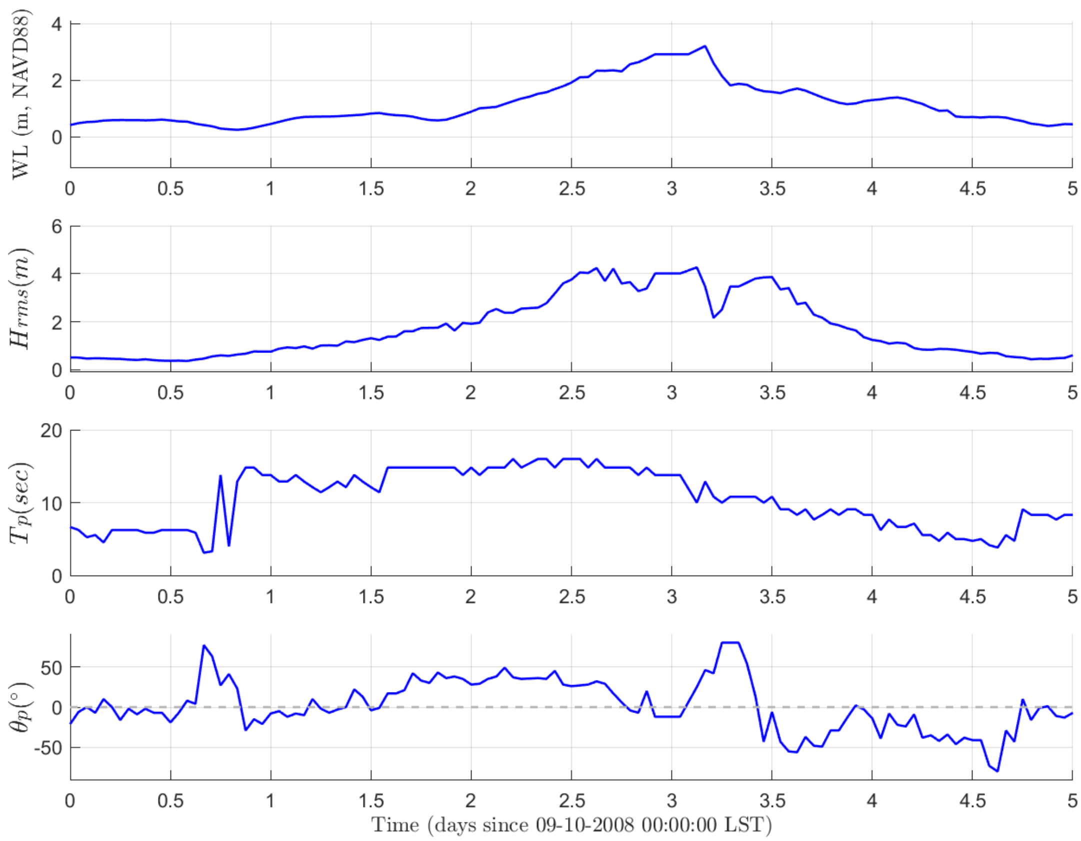

Figure A-4. Hydrodynamic conditions during Hurricane Ike measured by NOAA NDBC buoy 42035 in 17 m water depth offshore of Galveston Island.

Single-Dune Performance

In this section profile evolution of a single dune under storm forcing conditions are shown. While a 14-ft high dune with otherwise similar geometry to the USACE dune design can withstand the 10-year proxy storm (Figure A-5), it is eroded completely under Hurricane Ike conditions (30-year return value). Even a 17-ft high single dune is eroded completely by Hurricane Ike conditions. Adding a solid core inside the 17-foot high dune allows the dune to remain functional under Hurricane Ike conditions but with complete exposure of the seaward slope of the core structure (Figure A-6).

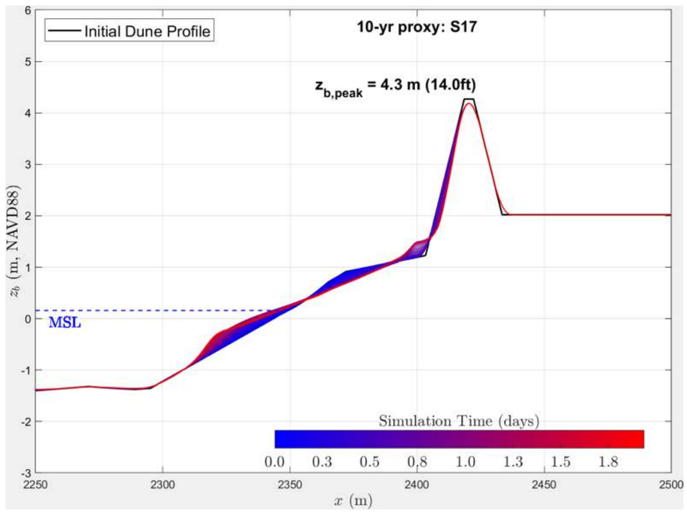

Figure A-5. Modeled beach and dune profile evolution of single dune (14-ft crest elevation) with 10-year proxy storm forcing shown in Figure A-3.

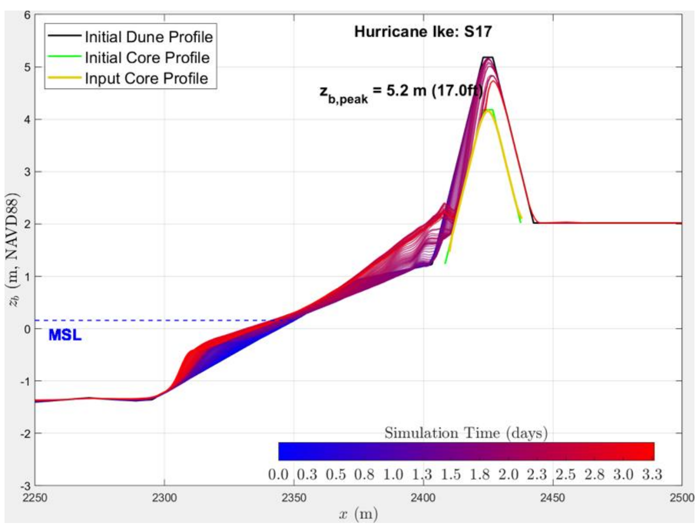

Figure A-6. Modeled beach and dune profile evolution of single dune (17-ft crest elevation) including core-enhancement with Hurricane Ike forcing shown in Figure A-3. Note that without the core-enhancement, the same dune was severely overtopped and eroded around the peak of the storm. The exposed seaward slope of the core structure helped prevent that in the result plot shown here.

Dual-Dune Performance (12/14-ft crest elevation)

The USACE proposed dual-dune design with 12- and 14-ft crest elevations, respectively, can withstand the 10-year proxy storm conditions with only minor erosion of the seaward dune face (Figure A-7). The dunes do not survive Hurricane Ike conditions and severe erosion and overtopping commence even before the peak of the storm. Hardened core structures included in both dunes are exposed during Ike conditions (Figure A-8).

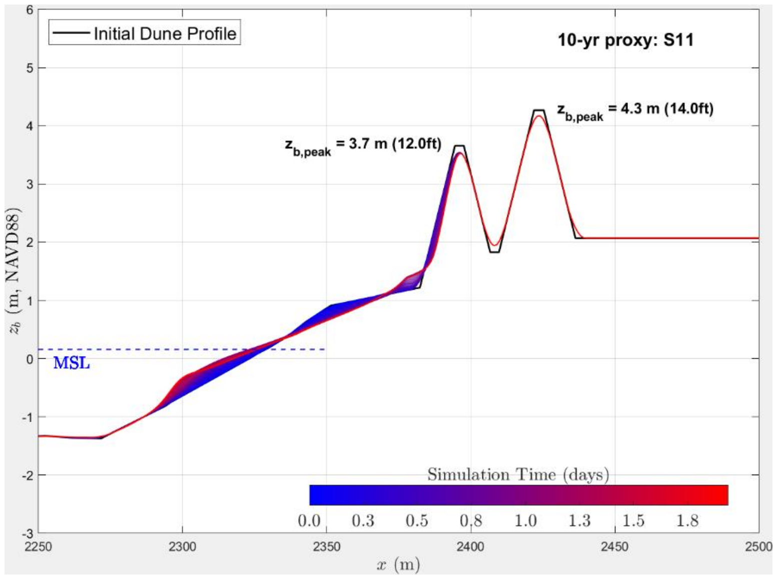

Figure A-7. Modeled beach and dune profile evolution of a dual-dune design (12/14-ft crest elevations) for 10-yr proxy storm forcing shown in Figure A-2.

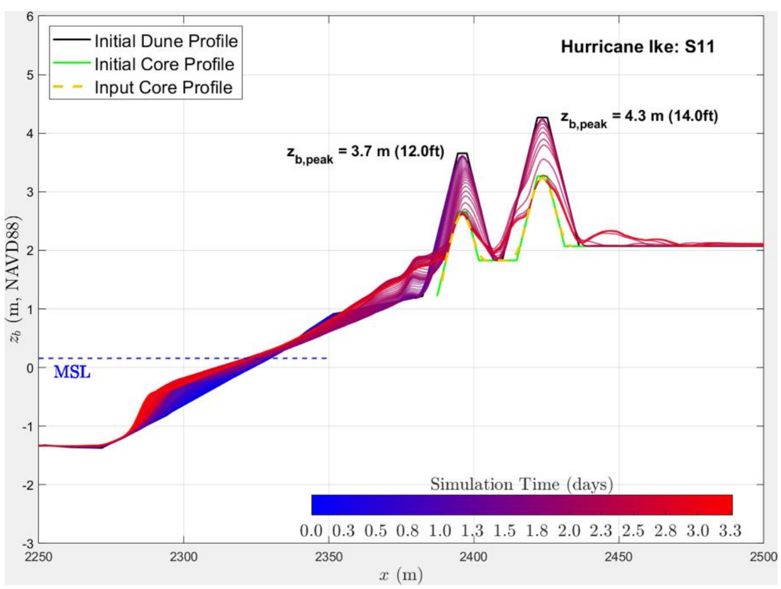

Figure A-8. Modeled beach and dune profile evolution of dual-dune design (12/14-ft crest elevations) including core-enhancements with Hurricane Ike forcing shown in Figure A-2. Note that without the core-enhancement, the same dune system was severely overtopped and eroded even before the peak of the storm.

Dual-Dune Performance (15/17-ft crest elevation)

Increasing the dual-dune elevations to 15 and 17 ft, respectively, for the seaward and landward dune, improves the system's resistance against erosion somewhat. The profile evolution for 10-year proxy storm forcing is shown in Figure A-9 where only minor erosion on the seaward dune slope is noted. Hurricane Ike forcing leads to complete erosion of the seaward dune and some erosion (1-ft crest reduction) and overtopping of the landward dune (Figure A-10). This means a 15/17-ft dual-dune system may barely survive a 30-year return value storm but require major renourishment afterwards.

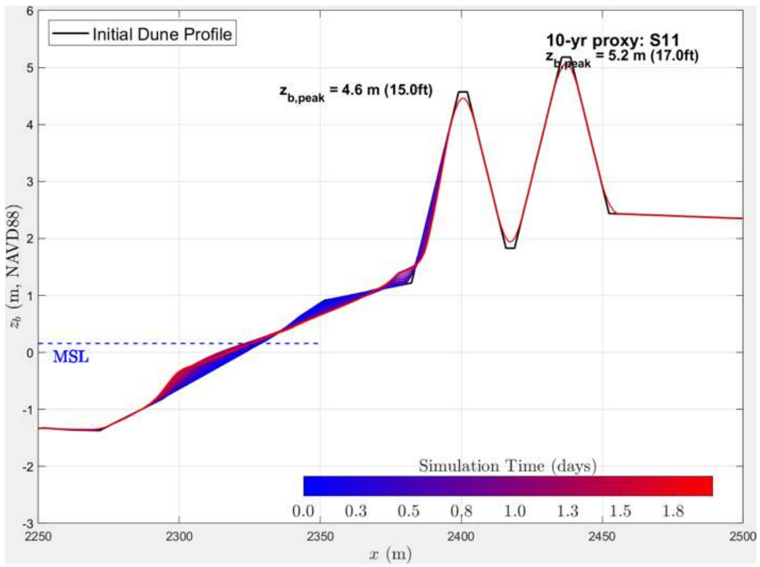

Figure A-9. Modeled beach and dune profile evolution of a dual-dune (15/17-ft crest elevations) for 10-yr proxy storm forcing shown in Figure A-2.

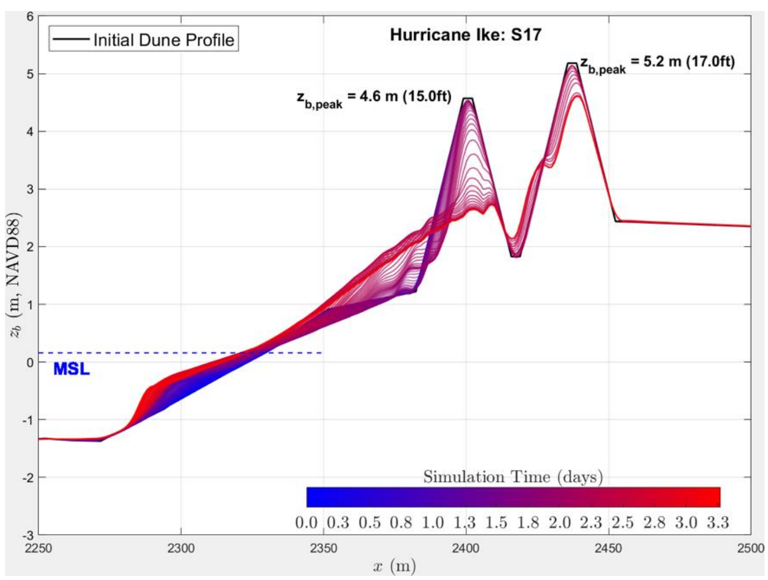

Figure A-10. Modeled beach and dune profile evolution of a dual-dune (15/17-ft crest elevations) for Hurricane Ike forcing shown in Figure A-3. The seaward dune helps protect the landward dune somewhat from eroding but crest elevation reduction over 1 ft is still apparent in the landward dune.

If dual cores are implemented, the landward dune erosion is mostly prevented due to the fact that the core of the seaward dune remains intact (Figure A-11).

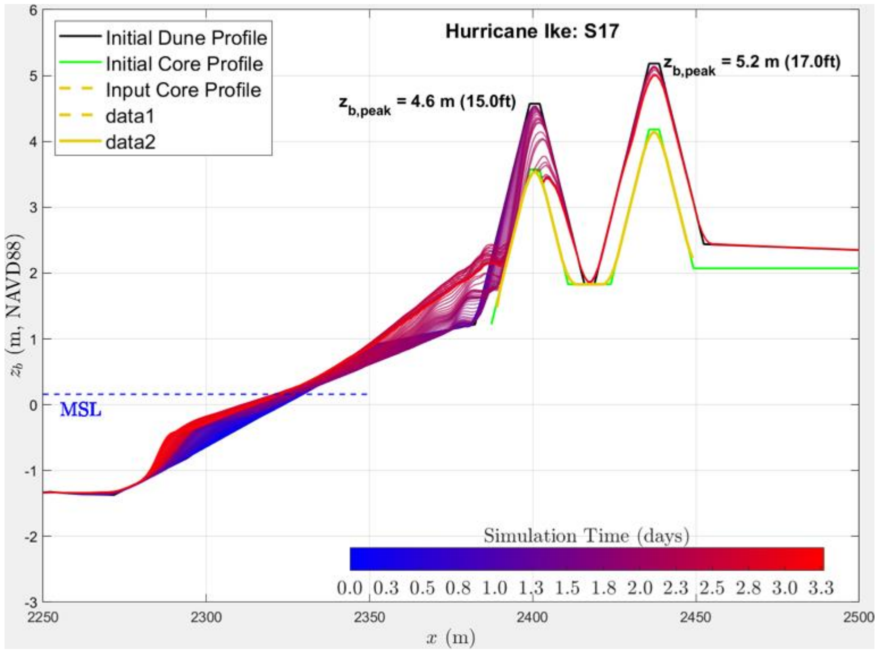

Figure A-11. Modeled beach and dune profile evolution of dual-dune design (15/17-ft crest elevations) including core-enhancements with Hurricane Ike forcing shown in Figure A-3. Note that without the core-enhancement, the seaward dune was completely eroded.

Dual-Dune Performance (modified crest widths and sea level rise scenario)

The following examples of CSHORE simulations investigate a limited range of geometric and core-enhancement modifications to the USACE proposed dual-dune design. Simulations include performance under Hurricane Ike forcing using the NOAA NDBC buoy data as input as well as increases in crest width and crest height of the dual-dune system (e.g., Figures A-12, A-14). Both single seaward and landward dune core-enhancements are tested (e.g. Figures A-13, A-15, A-17). Finally, the effects of a 2.1-ft sea level increase for enlarged dual-dunes with single landward and seaward dune core-enhancement, respectively, are shown (e.g., Figures A-16, A-17).

The modification to the dual-dune system shown in Figure A-12 is a doubling of the crest width in both the seaward and landward dune.

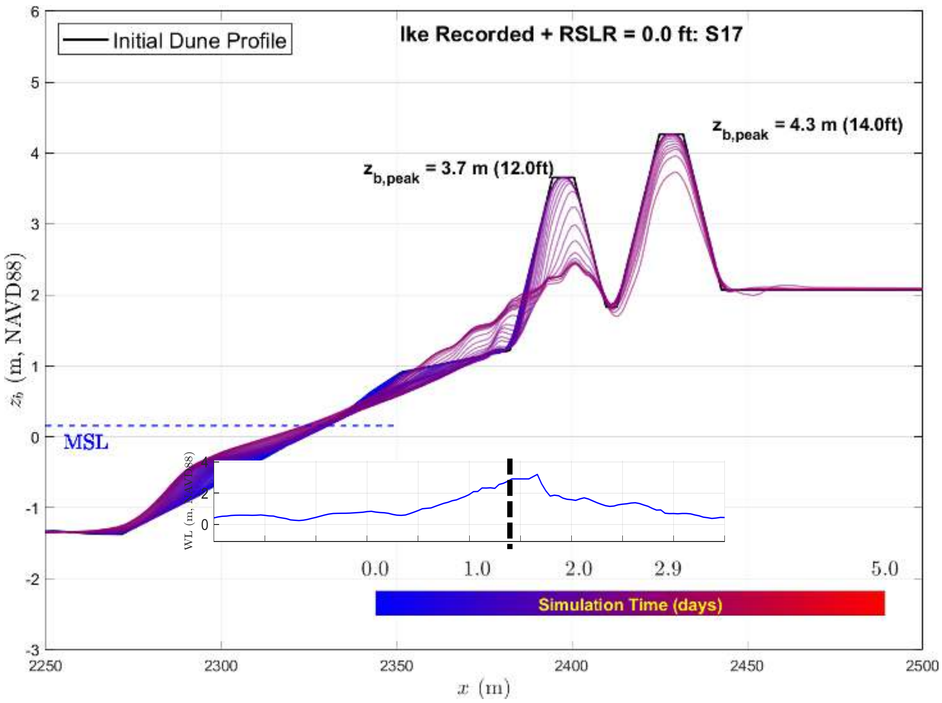

Figure A-12. Modeled beach and dune profile evolution of dual-dune design (12/14-ft crest elevations, double crest widths) with Hurricane Ike forcing shown in Figure A-4 and no sea level increase. Note that both dunes are severely overwashed well before the peak of the storm and water would continue to overtop the system for at least 10 hours. The simulation results are only shown up until the vertical black dashed line in the inset figure because past that point the dunes are destroyed and the simulation results become unrealistic.

Figure A-13 shows the same setup and forcing as Figure A-12 except that the seaward dune includes the core-enhancement. This leads to exposure of the core in the seaward dune under Hurricane Ike conditions, as well as delayed and reduced erosion of the landward dune.

Increasing both the width and height of the dual dunes helps increase erosion and flooding resistance. In Figure A-14 the dune profile evolution for a dual-dune system with 15/17-ft elevations and doubled dune crest widths is shown. The seaward dune is still completely eroded but its buffer function allows the landward dune to survive albeit with significant dune crest erosion.

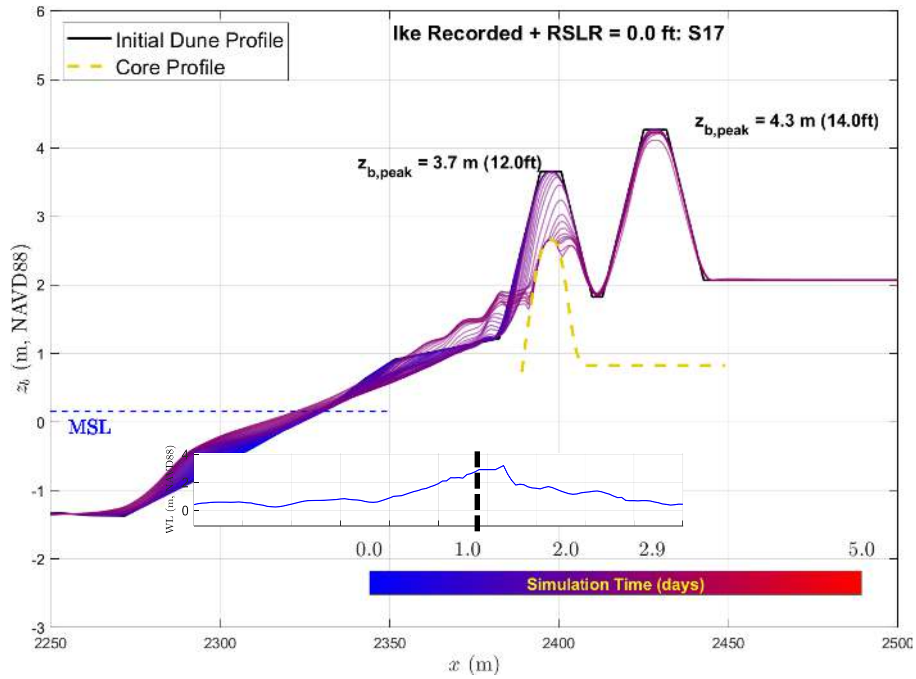

Figure A-13. Modeled beach and dune profile evolution of dual-dune design (12/14-ft crest elevations, double crest widths) and seaward dune core enhancement with Hurricane Ike forcing shown in Figure A-4 and no sea level increase. Note that the core structure delays and reduces erosion of the landward dune. The simulation results are only shown up until the vertical black dashed line in the inset figure to simplify comparison with the results in the previous figure.

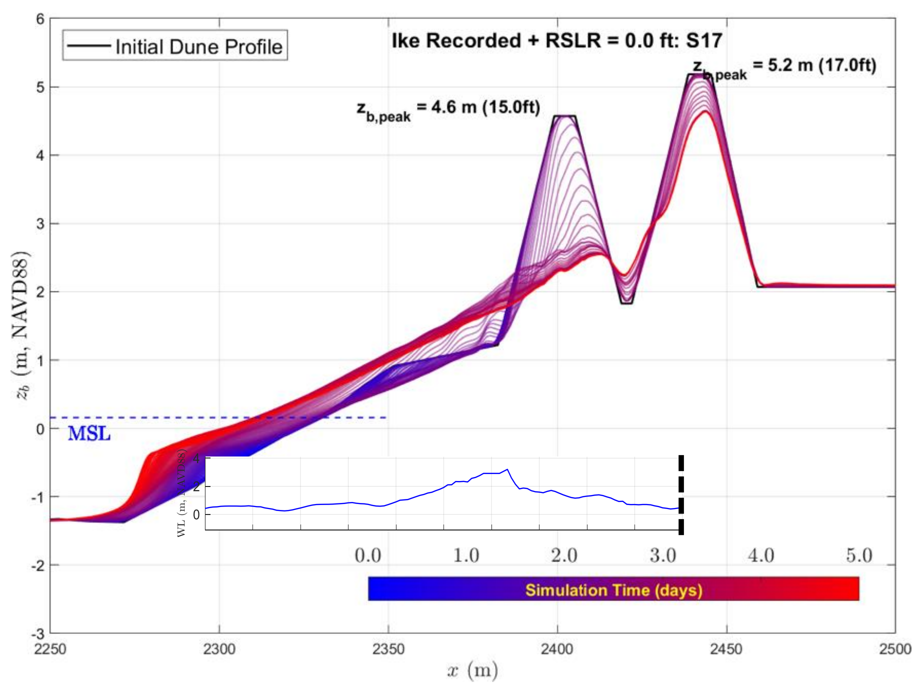

Figure A-14. Modeled beach and dune profile evolution of dual-dune design (15/17-ft crest elevations, double crest widths) with Hurricane Ike forcing shown in Figure A-4 and no sea level increase. The seaward dune is completely destroyed. The landward dune crest elevation is eroded by about 2 ft but the dune remains.

Figure A-15 shows the same scenario as Figure A-14 but now with a core-enhanced seaward dune. The core-enhancement is exposed during Hurricane Ike conditions and its sand covered crest is mostly eroded. The landward dune remains intact without major erosion.

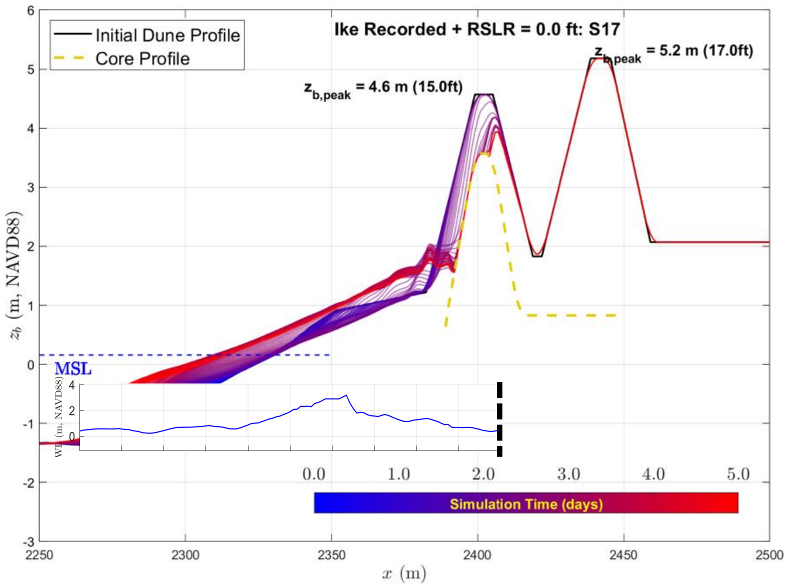

Figure A-15. Modeled beach and dune profile evolution of dual-dune design (15/17-ft crest elevations, double crest widths) and seaward dune core enhancement with Hurricane Ike forcing shown in Figure A-4 and no sea level increase. The enhanced core in the seaward dune is exposed and the dune crest erodes but the landward dune survives and remains intact.

For the 100-year proxy storm conditions and a sea level increase of 2.1 ft, the dual-dune system with increased crest heights and crest widths including a seaward dune core-enhancement performs as shown in Figure A-16. Under those conditions, the seaward core is completely exposed, the seaward dune crest cover eroded, and even the landward dune is substantially eroded and overtopped leading to a 4-ft crest reduction (Figure A-16).

In Figure A-17, the single core-enhancement has been placed in the landward dune instead of the seaward dune and the seaward dune crest width has not been increased, only the landward dune crest has been widened by a factor of two compared to the original USACE dune crest widths. The forcing conditions remain the same as for the Figure A-16 results (100-year proxy storm, 2.1-ft sea level increase). Under those conditions the seaward dune erodes completely and the landward dune core is exposed, leaving the 14-ft solid core as the maximum crest elevation against storm surge and wave overtopping impact.

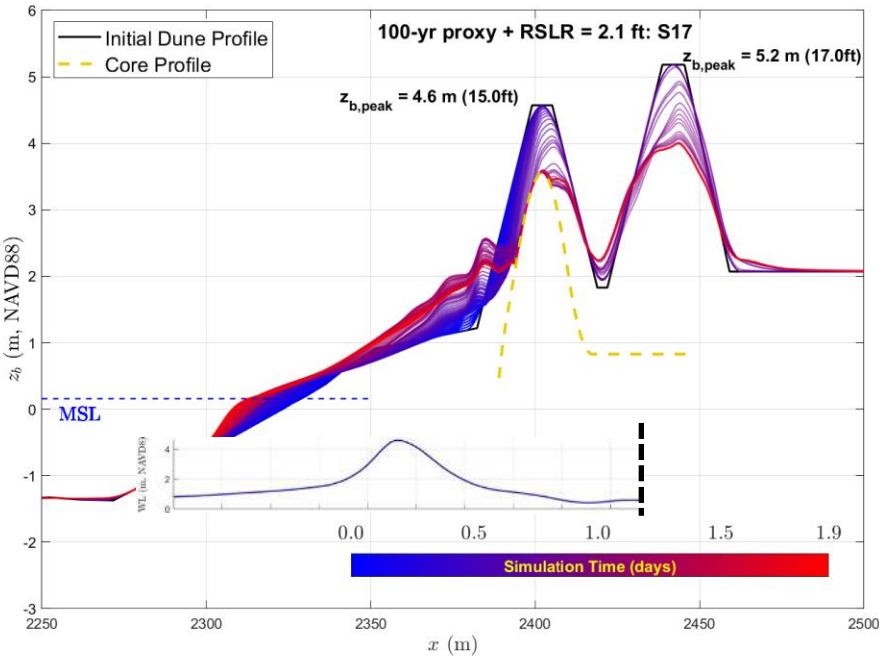

Figure A-16. Modeled beach and dune profile evolution of dual-dune design (15/17-ft crest elevations, double crest widths) and seaward dune core enhancement with 100-year proxy storm forcing shown in Figure A-3 and 2.1 ft sea level increase. The more energetic hydrodynamic forcing conditions coupled with the sea level increase reduces the landward dune crest by about 4 ft. Without the core protection both dunes are wiped out.

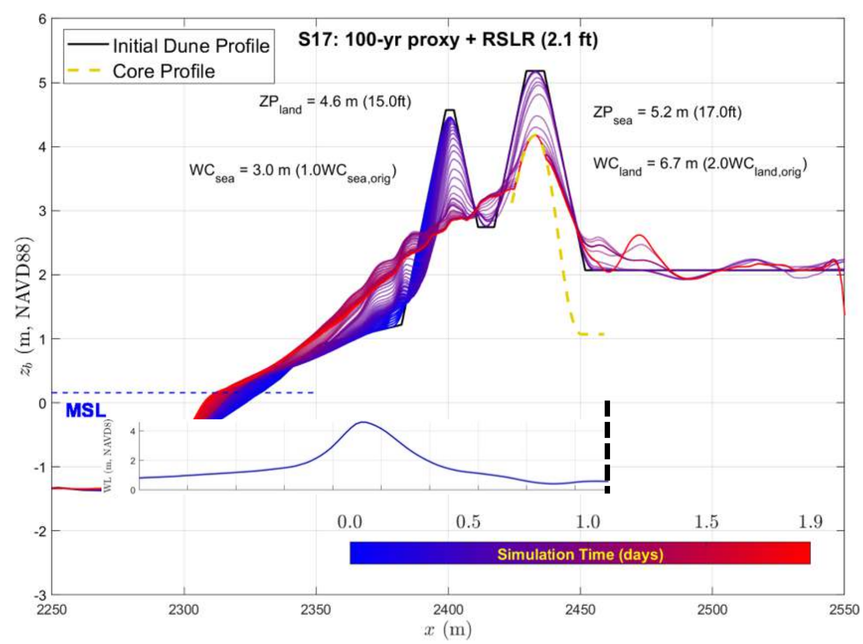

Figure A-17. Modeled beach and dune profile evolution of dual-dune design (15/17-ft crest elevations, double landward dune crest width) and landward dune core enhancement with 100-year proxy storm forcing shown in Figure A-3 and 2.1 ft sea level increase. The seaward dune is completely eroded and the core structure in the landward dune exposed. The solid core protection at 14 ft crest elevation remains intact to limit flooding.

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Harter, C., & Figlus, J. (2017). Numerical modeling of the morphodynamic response of a low-lying barrier island beach and foredune system inundated during Hurricane Ike using XBeach and CSHORE. Coastal Engineering, 120, 64–74. https://doi.org/10.1016/j.coastaleng.2016.11.005

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Johnson, B. D., Kobayashi, N., & Gravens, M. B. (2012). Cross-Shore numerical model CSHORE for waves, currents, sediment transport and beach profile evolution (Technical Report ERDC/CHL-TR-12-22). Engineer Research and Development Center.

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Appendix B: Cost-Effectiveness of Implementing the Ike Dike

Introduction

This appendix examines the cost-effectiveness of making two improvements to the coastal spine component of the USACE Plan, in essence adopting the Ike Dike coastal spine concept. The improvements are: 1) implementing a stronger fortified core-enhanced dune as the land barrier on both Galveston Island and Bolivar Peninsula, such as the fortified dune described in Chapter 4, and 2) adding a western section to the coastal spine, which includes a fortified dune on Follets Island and a gate system at San Luis Pass. The elevation of both improvements is 17 ft NAVD88, which is the elevation of the solid core in the fortified dune. Analysis done by Jackson State University (JSU) indicates that, for a 100-yr proxy storm and sea level rise of 2.4 ft, a 17-Ike Dike will reduce 100-yr water levels inside Galveston Bay by another 3 to 4 ft, and by 3 to 6 ft in West Bay, compared to the USACE Plan. This magnitude of peak surge reduction is expected to produce a considerable reduction in residual damage, compared to the USACE Plan, and provide a much higher level of protection for the region.

A wall-in-dune concept was adopted to estimate the cost of a fortified dune. The solid core is an inverted T-wall, which is embedded in a sand dune; this type of dune is illustrated in Figure B-1. This choice for the solid core was made because there were sufficient data provided in the USACE Feasibility Report to make a cost estimate. Cost data were available for inverted T-walls having a crest elevation of 17/18 ft for the Clear Lake and Dickinson wall/gate systems. Other choices for the solid core are possible, and another type of core might be less costly. Other options/combinations of core systems (e.g., clay dike, rubble mound, etc.) would reduce the volume of sand further and thus save costs if sand is assumed the most expensive material.

All equivalent average annual damage data that are cited here were extracted from Table 23 in Appendix E-1 of the USACE Feasibility Report; data in Table 23 are for the intermediate sea level rise scenario, which is consistent with the future sea level considered by JSU. All damage data reflect average annual damage values for residential and commercial properties, computed by USACE for a 50-yr period of economic analysis. Table B-1 shows cost data for the Coastal Storm Risk Management (CSRM) elements of the USACE Plan, and the total cost for all elements. Cost data were extracted from the spreadsheets in Annex 22 to Appendix D of the Feasibility Report.

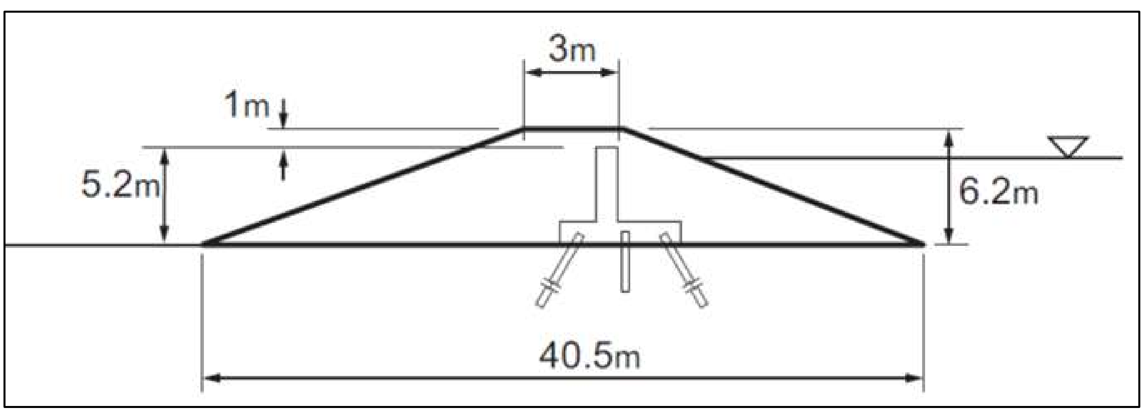

Figure B-1. Cross-section for a fortified dune having an inverted T-wall as the solid core.

Table B-1. Costs for Coastal Storm Risk Management (CSRM) Elements of the USACE Plan

USACE Plan Element	First Cost	Fully Funded Cost
Bolivar Roads gate system	$13.88B	$21.68B
Galveston Ring Barrier	$3.30B	$5.71B
Clear Lake gate	$1.52B	$2.77 B
Dickinson gate	$879M	$1.65B
Bolivar Beach and Dune (initial)	$1.34B	$1.87 B
West Galveston Beach and Dune (initial)	$1.20B	$1.66 B
Bolivar Periodic Renourishment	$671M	$3.13 B (7 renourishments)
West Galveston Renourishment	$359M	$1.70 B (6 renourishments)
Non-structural measures	$220M	$0.422B
Total	$23.37B	$40.59B
Clear Lake inverted T-wall (levees and floodwalls cost line item)		$232M
Dickinson inverted T-wall (levees and floodwalls cost line item)		$109M

Cost of a Fortified Dune Land Barrier

Several assumptions were made to facilitate estimation of the cost for a fortified dune. One is that the volume of sand contained in the dual sand dune system of the USACE Plan is sufficient to cover the solid core of a fortified dune and, if desired, a smaller front dune as is included in the USACE Plan. A second assumption is that the renourishment that is required for the fortified dune will be significantly less than the renourishment estimated for the much lower dual sand dunes n the USACE Plan; a 50% reduction in cost is assumed (thus use of the 0.5 multiplication factor in step 1 below). Compared to the lower dunes in the USACE Plan, the higher fortified dune will experience much less frequent overtopping, erosion and degradation of the dune crest, and subsequent loss of sand volume due to overtopping and overwash.

The cost to build a fortified dune, with an inverted 17-ft high T-wall as its solid core, and with sand cover, is estimated using the following steps:

1) Compute the cost of a mile of beach/dune system in the USACE Plan. $3.53B (1.87B + 1.66B) is the fully funded cost for initial construction of 43 miles of beach/dune on both Bolivar Peninsula and Galveston Island. The per-mile cost for initial construction is $82M per mile. Total renourishment cost for the life of the project is estimated as 0.5 x (3.13B + 1.7B)/ 43 miles = $56M per mile. The total cost for sand in a fortified dune is the sum of initial construction and all renourishment, **$138M per mile.**

2) Compute the cost of a 17-ft inverted T-wall, based on the levees and walls line item cost for the Clear Lake and Dickinson wall/gate systems.

    - Clear Lake - $232M fully funded construction cost x 1.25 factor for other costs = $290M / 1.5 mile length = $193M per mile

- Dickinson - $109M fully funded construction cost x 1.25 for other costs = $136M / 0.7 mile length = $195M per mile

Use **$195M/mile** for the cost of constructing the inverted T-wall solid core.

3) Compute the total cost to build and renourish a fortified dune as the land barrier, $138M/mile (sand) + $195M/mile (solid core) = **$333M/mile**

Total cost to build and renourish 43 miles of dual sand dune in the USACE Plan is $8.36B.

Total cost to build and renourish 43 miles of fortified dune is $14.32B, an increase of $5.96B.

Total cost to build and renourish 18 miles of dual sand dune on Galveston Island is $3.36B

Total cost to build and renourish 18 miles of fortified dune on Galveston Island is $5.99M, an increase of $2.63B.

Total cost to build and renourish 25 miles of dual sand dune on Bolivar Peninsula is $5.0B

Total cost to build and renourish 25 miles of fortified dune on Bolivar Peninsula is $8.33B, an increase of $3.33B.

Cost of a Western Section to the Coastal Spine

The cost to add 13 miles of fortified dune to Follett's Island is $333M/mile x 13 miles = $4.33B.

The cost for a small gate system at San Luis Pass, a Delft University of Technology (TUDelft) estimate, is $330M. Add 25% for other costs to arrive at a total cost of $413M.

Total cost to add a western section to the coastal spine in the USACE Plan is $4.74B.

Cost-Effectiveness of the USACE Plan

The total fully funded cost for all Coastal Storm Risk Management elements in the USACE Plan is $40.59B (see Table B-1). For the intermediate sea level rise scenario, this investment achieves $1.7B in average annual damage reduction; the average annual residual damage is $1.15B. Note: the amount of damage reduced, which is cited in the USACE Feasibility Report, is overestimated and the residual damage is underestimated because of the flaw in the USACE storm surge modeling discussed in Chapter 2.

As a cost-effectiveness metric, an indicative Benefit/Cost ratio (BCR) is defined, where:

Benefit = the reduction in average annual damage produced by some protective measure, multiplied by 50 yrs to reflect a 50-yr period of analysis

Cost = fully-funded cost of the protective measure over a 50-yr period of analysis

The larger the BCR for a given protective measure, the more cost-effective it is.

Using this metric, the BCR for the entire USACE Plan is ($1.7B x 50)/40.59B or **2.09**. In light of the USACE surge modeling flaw, the BCR for the USACE Plan is likely to be significantly lower than this value.

Damage Reduction from Improvements to the USACE Plan

To assess the cost-effectiveness of improvements to the USACE Plan, the additional cost of making improvements is compared to the further reduction in residual damages that is achieved with the improvements. Costs and damage reduction are then used in calculating the BCR for the improvements.

It is not possible in this review to separate the beneficial effects of implementing a higher fortified dune from benefits attributable to adding a western section. Therefore, for this analysis, it is assumed that improvements made to the coastal spine fronting West Bay only serve to reduce residual damage in West Bay, and the same for Galveston Bay. However, based on information in Appendix A and the JSU (2018) report, the benefit of improvements made in West Bay is also realized in Galveston Bay. Therefore, in this analysis, the cost-effectiveness of improvements made to the spine fronting West Bay is understated, and the value of improvements made to the spine in Galveston Bay is overstated.

Residual damage for the USACE Plan, for the intermediate sea level rise scenario, is $1.15B, distributed as 55% in West Bay ($633M) and 45% in Galveston Bay ($518M). Improvements to the USACE Plan will reduce the residual damage in each bay by a significant, but unknown, amount. In light of the large reductions in 100-yr surge levels expected for the 17-ft Ike Dike, compared to the USACE Plan, cost-effectiveness is examined for two levels of damage reduction, 50% and 75%.

For a 75% reduction in residual damage, damage reduction for West Bay is 0.75 x $633M, or $475M.

For a 50% reduction in residual damage, damage reduction for West Bay is 0.5 x $633M, or $317M.

For a 75% reduction in residual damage, damage reduction for Galveston Bay is 0.75 x $518M, or $389M.

For a 50% reduction in residual damage, damage reduction for Galveston Bay is 0.5 x $518M, or $259M.

Cost-Effectiveness of West Bay Improvements

The cost of improvements in West Bay is calculated as the cost of the western section ($4.74B) plus the added cost to build and renourish 18 miles of fortified dune on Galveston Island, $2.63B. The total cost for West Bay improvements is $7.37B.

Assuming 75% reduction in damages, the BCR for the West Bay improvements is (0.475B x 50)/7.37B = **3.22.**

Assuming 50% reduction in damages, the BCR for the West Bay improvements is (0.317B x 50)/7.37B = **2.15**.

For either percentage of damage reduction, the West Bay improvements appear to be more cost-effective that the USACE Plan in its entirety, particularly in light of the overestimate of damage reduction for the USACE Plan due to the surge modeling flaw, and neglecting the benefit of West Bay improvements to Galveston Bay.

Cost Effectiveness of Galveston Bay Improvements

The cost of improvements in Galveston Bay is calculated as the added cost to build and renourish 25 miles of fortified dune on Bolivar Peninsula. The total added cost for Galveston Bay improvements is $3.33B.

Assuming 75% reduction in damages, the BCR for the Galveston Bay improvements is (0.389B x 50)/3.33B = **5.84**.

Assuming 50% reduction in damages, the BCR for the Galveston Bay improvements is (0.259B x 50)/3.33B = **3.89**.

For either percentage of damage reduction, the Galveston Bay improvements appear to be more cost-effective that the USACE Plan in its entirety, even if the benefit to Galveston Bay is somewhat overstated.

Overall Cost-Effectiveness of Improvements to the USACE Plan

The additional cost to build and renourish 43 miles of fortified dune is $5.96B. The additional cost to add a western section of the coastal spine to the USACE Plan is $4.74B. The total added cost to implement both improvements and implement a robust 17-ft Ike Dike coastal spine is $10.7B.

Average annual residual damages for the USACE Plan are $1.15B.

Assuming 75% reduction in damages (0.75 x $1.15B = $863M), the BCR for all improvements is (0.863B x 50)/10.7B = **4.03**.

Assuming 50% reduction in damages (0.5 x $1.15B = $575M), the BCR for all improvements is (0.575B x 50)/10.7B = **2.69**.

Making both improvements appears to be more cost-effective that the USACE Plan in its entirety.

In addition to direct benefits, in terms of reductions in residual damage derived from improvements to the USACE coastal spine, significant costs are avoided, i.e. saved. One is the reduction in the volume of sand needed to renourish the fortified dune, estimated to be $2.4B. In addition, inside the bays, significant costs are avoided by strengthening the coastal spine. A stronger first line of defense will reduce the need for, or extent, height, strength and cost of all in-bay measures, including the Galveston Ring Barrier, the second lines of defense at Clear Lake and Dickinson, and all non-structural measures. A 10% cost savings for in-bay measures would be $1B, a 25% savings would be $2.5B.

The USACE cost estimate for the Bolivar Roads Storm Surge Barrier is $13.8B. Independent estimates, presented in Chapter 3 suggest a more accurate estimate is $4.6B (and a bandwidth between $2.4B and $6.8B). The added cost to make both improvements and fully implement the 17-ft Ike Dike is $10.7B. This cost increase is roughly offset by the sum of a $7B to $11B overestimate for the cost of the Bolivar

Roads Barrier, $2.4B cost avoidance for renourishment volume, and $1B to $2.5B cost avoidances for in-bay measures. With a more realistic estimate for the Bolivar Roads Barrier, implementing the two improvements to the USACE coastal spine is not expected to change the overall cost estimate by much ($23.37B for the Plan elements shown in Table B-1); however, the improvements will be much more effective in reducing damage for the entire region than the USACE Plan. We are concerned that the high estimate for the Bolivar Roads Barrier adversely skews the overall benefit-cost ratio, leading to limited consideration of other means for reducing damage in the region.

Appendix C. Cost Estimation of the Bolivar Roads Barrier Using Recent Methods for Cost Estimation

This appendix presents further information with respect to the cost estimate for the proposed storm surge barrier at Bolivar Roads. For these cost estimates the method from Kluijver et al. (2019) has been used. The model is based on the costs of existing barriers around the world, and the dimensions of the various barrier features. It utilizes the following formula:

$$Cost = €157{,}000 \text{ x } Navigable\ Area + €102{,}000 \text{ x } Auxiliary\ Area + €26{,}000 \text{ x } Dam\ Area$$

Auxiliary area refers to the environmental gates; all areas in m^2; price levels in 2019 Euros. The exchange rate at this moment is € 1 = $ 1.20 and this value has been assumed here.

The above formula does include planning, engineering and design costs. It produces an expected (50%) cost value. A 90% confidence interval can be defined based upon the dataset analyzed with the following slope intervals: +/- €60,000 on the Navigational area (NA) term coefficient, +/- €54,000 on the Auxiliary flow area (AA) term coefficient and +/- €13,500 on the Dam or static term (DA) term coefficient (Kluijver et al 2019).

As inputs to the formula information on the gates has been derived from the engineering report and Annex 19. For estimating the height of navigational and environmental gates the channel depths plus an additional 10 ft was used. This estimate presented here does not include the earthen levee on Bolivar peninsula, nor visitor building. Table C-1 presents the barrier dimensions. Table C-2 presents the cost estimates based on these barrier dimensions. Table C-3 summarizes some main metrics related to the width of the barrier and its various elements. Table C-4 presents an alternative cost estimate using the unit cost proposed by Mooyaart (2017) which is based on a unit cost of 2.47 MEuro/m per meter gate width.

Table C-1. Barrier elements and dimensions

Section	amount	width (ft)	width (m)	total width (m)	Avg. height (ft)	Avg. height (m)	total cross section (m2)
Combi wall	1	5300	1616	1616	22	6,7	10838
Environmental gate shallow	16	96	29	468	26,5	8,1	3783
Environmental gate large 20ft	8	300	91	732	30	9,1	6692
Environmental gate large 40ft	7	300	91	640	50	15,2	9760
Navigational gate - large	2	650	198	396	70	21,3	8459
Navigational gate - small	2	125	38	76	50	15,2	1162

Table C-2. Barrier elements and dimensions and costs according to the model of Kluijver et al (2019)

Section	total cross section (m2)	Unit cost (E/m2 avg)	Unit cost (low)	Unit cost (high)	Total cost (Euro Avg)	total Cost (ME)	Total cost (M$)	Total cost (ME low)	Total cost (ME high)
Combi wall	10838	26000	12500	39500	2,82E+08	282	338	135	428
Environmental gate shallow	3783	102000	48000	156000	3,86E+08	386	463	182	590
Environmental gate large 20ft	6692	102000	48000	156000	6,83E+08	683	819	321	1044
Environmental gate large 40ft	9760	102000	48000	156000	9,96E+08	996	1195	468	1523
Navigational gate - large	8459	157000	97000	217000	1,33E+09	1328	1594	820	1835
Navigational gate - small	1162	157000	97000	217000	1,82E+08	182	219	113	252
Total cost (MEuro)						**3856**		**2040**	**5673**
Total cost (M$)						**4627**	**4627**	**2448**	**6807**

Table C-3. Width of various barrier sections

Element	width (m)	Element	width (m)
total with combi wall	3929	navigational gates	473
total without combi wall	2313	environmental gates	1840
navigational gates	473	Dam	1616

Table C-4. Alternative cost estimate using the unit cost proposed by Mooyaart (2017) which is based on a unit cost of 2.47 MEuro/m per meter gate width.

	Expected	Lower bound	Upper bound
Cost (ME)	5713	2313	9251
Cost (M$)	6855	2775	11101

References

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Samuel Brody

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Cherie Coffman

Ms. Cherie Coffman is a senior administrative coordinator at Texas A&M University at Galveston. Ms. Coffman began her career at A&M Galveston in 1992, as assistant to the VP for Administration, but within a year was transferred to the job of assistant to the head of the Galveston campus. She served in that position for 19 years. In 2011, she transferred to work with Bill Merrell on the Ike Dike project, providing the Galveston's campus's contribution to this important project. She quickly assumed the principal responsibilities for outreach and coordination with Galveston county leaders, national academic partners, Dutch researchers, and the print and television media. Particularly important is her central role in coordinating tours of the Netherlands' coastal protection complex for Texas legislators and decision makers. In addition to Ike Dike work, her duties have expanded into serving the entire Center for Texas Beaches and Shores in their important mission to reduce flood risk in Texas.

Bruce Ebersole

Mr. Ebersole holds a B.S. degree in civil engineering and a M.C.E. degree in civil engineering (with an emphasis in coastal engineering) from the University of Delaware. He worked as a supervisory research engineer with the U.S. Army Engineer Research and Development Center (ERDC) Coastal & Hydraulics Laboratory from 1988 until 2011, first as Chief, Coastal Processes Branch from 1988 to 2004, then as Chief, Flood and Storm Protection Division, leading a division of 110 employees with an annual work program of $25 million, until his retirement in 2011. He was inducted into ERDC's Waterways Experiment Station (WES) Gallery of Distinguished Civilian Employees in 2019. From 2009-2014 he served as a member of the Advisory Board, Department of Homeland Security, Coastal Hazards Center of Excellence. From 2008-2011, Mr. Ebersole was the U.S. Army Corps of Engineers representative to the White

House Office of Science and Technology Policy, Subcommittee on Disaster Reduction, Coastal Inundation Working Group. He was a contributing author to the book, Engineering Investigations of Hurricane Damage, Wind Versus Water, *Basic Storm Surge, Wave, and Flooding Principles*, American Society of Civil Engineers, 2014. Since 2014, Mr. Ebersole has served as a Senior Research Associate at Jackson State University, where he is working with partners at Texas A&M University-Galveston Campus and TU Delft to evaluate and refine the Ike Dike concept for reducing hurricane flood risk in the Houston-Galveston region.

Jens Figlus

Dr. Jens Figlus is a civil/coastal engineer and Associate Professor in the Department of Ocean Engineering at Texas A&M University. Dr. Figlus heads the Coastal Engineering Laboratory (CEL) on A&M's Galveston Campus and is a faculty fellow with the Center for Texas Beaches and Shores (CTBS) and the Institute for a Disaster Resilient Texas (IDRT). He received his Masters and Ph.D. degrees in civil engineering with an emphasis on coastal engineering from the University of Delaware. Since joining Texas A&M University in 2012, Dr. Figlus has been conducting engineering research and teaching undergraduate and graduate students about coastal engineering and related subjects. He teaches classes related to coastal engineering, fluid dynamics, geotechnical engineering, and ocean measurements and is a faculty mentor for undergraduate research scholars. Dr. Figlus' research focuses on improving our understanding of coastal system processes and engineering approaches to reduce the risk of coastal flooding and erosion. He is an expert in field measurement techniques, laboratory experiments, and numerical model analysis related to storm impacts on barrier islands and dunes, coastal hydrodynamics, sediment transport, and morphodynamics. Together with his team he runs the CEL movable-bed wave flume research facility and deploys field instrumentation to capture wave, current, and sediment processes in nearshore and bay systems.

Bas Jonkman

Dr. Bas Jonkman is Professor of Hydraulic Structures and Flood Risk at TU Delft. Prof. Jonkman holds Msc and PhD degrees in civil engineering from Delft University. In the past he has worked for Rijkswaterstaat, Royal Haskoning and UC Berkeley. He has investigated the levee failures in New Orleans and other countries and has been involved in engineering and flood risk studies in several areas around the world. His research interests include flood risk analysis, and the (probabilistic) design of hydraulic infrastructures, such as flood defences and storm surge barriers. Dr. Jonkman is currently leading a number of national and international research projects focusing on nature-based flood protection, and the forensic investigation of causes and impacts of failures of flood defences. He was also the coordinator of a recently completed European project called BRIGAID (20 partners, 7.8M€), which focused on the development of innovative solutions to reduce the risks of floods, drought and extreme weather. He is currently an advisor for Rijkswaterstaat, a member of the Dutch Expertise

Network on Flood Protection (ENW), the Advisory Committee on Water (AcW) and is the chairman of the hydraulic engineering department of the Dutch association of engineers (KIVI).

Baukje Kothuis

Dr. Kothuis is a research associate in the Faculty of Civil Engineering, Hydraulic Structures and Flood Risk at TU Delft. Her research focuses on multi-functional flood defenses, transdisciplinary knowledge integration, and stakeholder inclusive design of structures and strategies for flood resilience. She manages multidisciplinary research projects on delta design and is coordinator for the Houston Galveston Bay case for TU Delft. She mentors students from TU Delft on long term research projects in Texas. She is editor of the publications 'Delft Delta Design – Houston Galveston Bay Region, Texas, USA'; 'Sustainable and Integrated Design of Multifunctional Flood Defenses'; and 'Delta Interventions'.

Yoon Lee

Dr. Yoonjeong Lee is a research scientist and a lecturer in the Institute for a Disaster Resilient Texas and the Department of Marine and Coastal Environmental Science at Texas A&M University, Galveston Campus. Dr. Lee received her Ph.D. in Urban and Regional Sciences from Texas A&M University. Dr. Lee joined the Ike Dike team in 2013 and have been involved in multiple projects related to flood risk reduction and mitigation. Her research focuses on urban flooding, flood risk communication, community outreach and education. Since 2016, Dr. Lee has been in charge of research and education exchange between TAMUG and TU Delft serving as the Education Program Director of the NSF PIRE Coastal Flood Risk Reduction Program. She teaches graduate courses in sustainable coastal management and resiliency, international flood risk mitigation strategies, and environmental planning.

Willam J. Merrell

Dr. William J. Merrell holds a B.S. in physics and a M.A. in mathematics from Sam Houston State University and a Ph.D. in oceanography from Texas A&M University. He is the George P. Mitchell chair of marine sciences at Texas A&M University at Galveston, Regents Professor and President Emeritus, TAMUG. He has been chair of the H. John Heinz III Center for Science, Economics and the Environment, vice chancellor for Strategic Programs of The Texas A&M University System, vice president for Research Policy of Texas A&M University, chair of the Ocean Studies Board, served on the Space Studies Board and the Board on Sustainability of the National Research Council and has held presidential appointments with the National Science Foundation. Among his awards are the Distinguished Achievement Medal from the Geosciences and Earth Resources Council and he is the only person to receive the Distinguished Service Award of the National Science Foundation twice. Following the devastation of Hurricane Ike, Dr. Merrell began the Ike Dike project to provide hurricane surge protection for the Upper Texas Coast including all of Houston and Galveston.

Tom Richardson

Mr. Tom Richardson is Executive Director of the Coastal Resilience Center of Excellence. He is an engineering graduate of The Citadel, the University of Miami, and the International Institute for Hydraulic and Environmental Engineering in Delft, The Netherlands. Beginning in 1972 at what is now the Coastal and Hydraulics Laboratory of the Engineer Research and Development Center, his career has focused on developing, performing and managing applied research in coastal and hydraulic engineering. Among other achievements, he designed and built the world's first portable hydraulic land-based system for bypassing sand at coastal inlets. He played a key role in developing the concept of Regional Sediment Management and in transitioning it to practice nationwide. Mr. Richardson served as the Principal Federal Liaison to National Research Council Committees on assessing the return on investment from applied R&D programs and on systems for making measurements in the coastal zone. He was Federal Co-Chair of the Gulf of Mexico Program's Coastal and Shoreline Erosion Committee and a Charter Organizer of the National Beach Preservation Technology Conference. For the past 10 years, he has been a Director of the American Shore and Beach Preservation Association and currently serves as Chair of its Government Affairs Committee. In 2009, Mr. Richardson retired as Director of the Coastal and Hydraulics Laboratory and began work at Jackson State University as Deputy Director of the Coastal Hazards Center of Excellence.

Youn-Kyung Song

Dr. Youn-Kyung Song is a research assistant professor at the Department of Ocean Engineering at Texas A&M University. Since joining the Coastal Engineering Laboratory (CEL) based in TAMU's Galveston campus in 2016, various coastal civil engineering research projects were carried out concerning the surface water impacts from both ocean wave and rainfall events on flooding, erosion and solid transportation across the populated beaches and seafront resident and business areas. The topics investigated include coastal surf and swash processes during the sequence of beach erosion and recovery after storm, rainwater runoff hydrologic impacts on low-lying coastal plains, effects of ship channel dredging, geomodification, and deep-drafted navigation on port, harbor and nearshore processes, and sediment dynamics associated with evolution of a nearshore dredge berm placement. Previously, her academic research studied the nearshore long-wave propagation and wave interaction with natural and built environment under intensified weather conditions. A combination of physical, numerical, and field campaigns are being used to investigate the structural and morphological responses to intense wave flows from both academic and industrial engineering perspectives.

Robert W. Whalin

Dr. Robert W. Whalin is Professor of Civil Engineering in the College of Science, Engineering and Technology at Jackson State University (JSU) and Director Emeritus of Engineer Research and Development Center. He serves as Director for Education, Coastal Resilience Center of Excellence, University of North Carolina sponsored by the U.S. Department of Homeland

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