Appendix: Memos of ongoing research on flood risk reduction in Galveston Bay area

1) RECONNAISSANCE LEVEL STUDIES ON A STORM SURGE BARRIER IN BOLIVAR ROADS (TU Delft, Lendering)

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Keywords: storm surge barrier, hurricanes, probabilistic analysis, flood defenses, coastal protection

BACKGROUND The Ike Dike comprises a coastal protection system across the Galveston and Bolivar Islands together with a storm surge barrier in the Bolivar Roads. The crossing of the Bolivar is identified as the main technical challenge of the Ike Dike system. A storm surge barrier is proposed as an appropriate solution here, which can remain open during normal conditions, for the purposes of navigation and tidal exchange, but needs to be closed during a hurricane.

OBJECTIVES The proposed storm surge barrier consists of two parts: a navigational section, which facilitates navigation during normal conditions, and an environmental section, which allows sufficient tidal exchange through the Bolivar Road to preserve ecology. Several studies were undertaken to determine the boundary conditions for the barrier and which type of barrier is best suitable for both sections. Conceptual designs are engineered which provide first insights in the design of the barrier.

APPROACH It is a prerequisite to have proper insight into the engineering boundary conditions. The key hydraulic parameter for this design is the maximum head difference, between the bay and the open coast (both positive and negative), after closure of the barrier. Another important aspect for the design of the barrier is the subsoil, upon which the barrier will be built. Based on studies of these boundary conditions options for both the navigation and environmental section are investigated.

BOUNDARY CONDITIONS To determine the hydraulic boundary conditions a probabilistic behaviour-oriented storm surge model is developed. The model couples meteorological forcing with hydrodynamic response and provides a first-estimate of storm surge within simplified semi-enclosed bays, like the Galveston Bay. The surge behavior in Galveston Bay under hurricane forcing is estimated using a simplified inlet-bay system such as studied by Lorentz (1926) and Dronkers (1964). The mathematical model consists of a circular bay with constant depth and a constant surface area, connected to an infinitely long and straight coast by an inlet channel with negligible storage (see Figure 2). It is recognized more detailed modeling is necessary to fine tune the numbers presented herein.

The surge height depends on the storm track and intensity, but also the coastal geometry and bathymetry. Two situations for the hydraulic have been applied in the conceptual design

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(see fig. 1). Landfall location 50 km west of Bolivar Roads is governing for the maximum positive head, which is about 10 meter, meaning that the water level at the Gulf of Mexico is higher than the water level in the Galveston Bay. A hurricane that makes landfall 250 km east of the inlet results in a maximum negative head of about 3 meter. If a negative head occurs it is recommended to open the barrier to release the head.

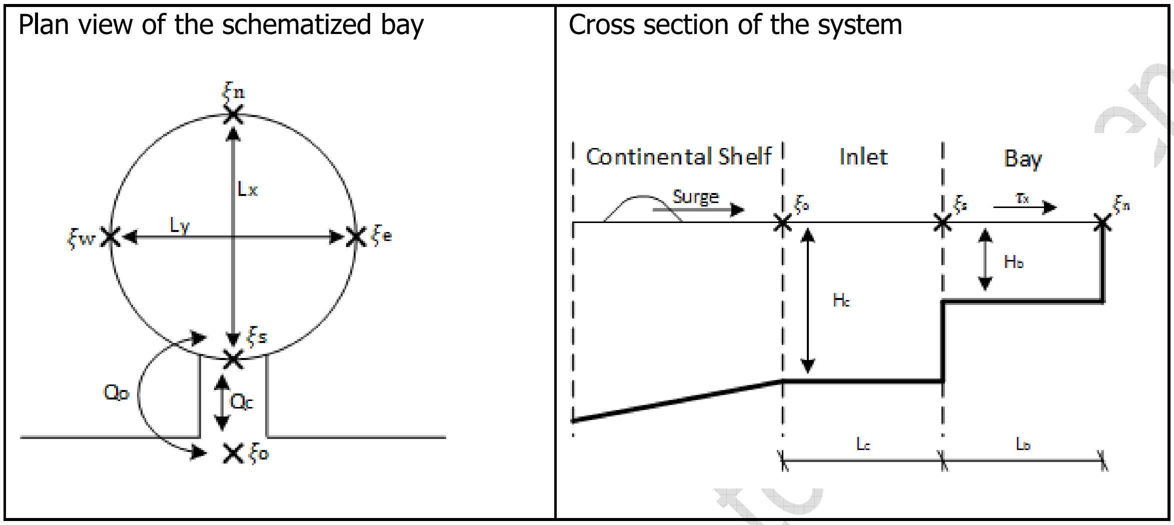

Figure 1: Simplified mathematical model for determination of surge behavior in Galveston Bay with water depth H [m], water level ξ [m], length L [m] and discharge Qc [m³/s].

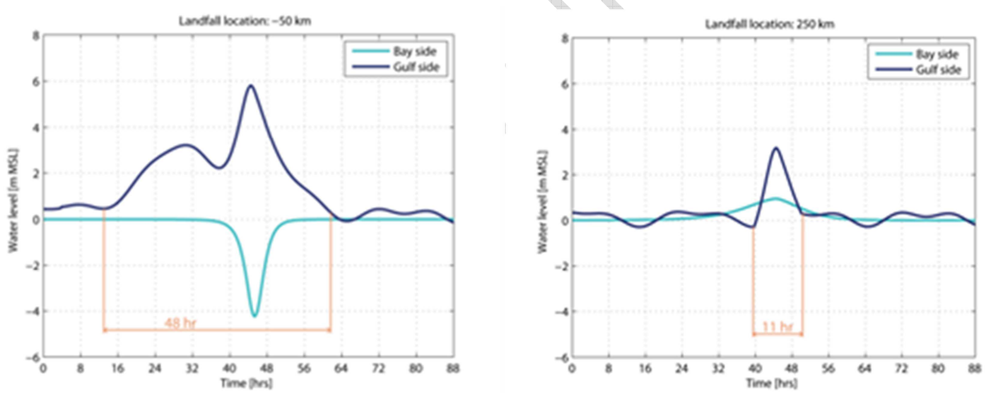

Figure 2: Maximum positive head (left) and negative head (right)

For hurricanes expected to make landfall within 250km (east or west) from Bolivar Roads the barrier should be closed approximately 32 hours prior to landfall to prevent substantial inflow into the Galveston Bay (see figure 4, left). In total the barrier should remain closed for at least 48 hours, without considering closing and opening at low tide.

The subsoil in Bolivar Roads consists mainly of soft and firm clay layers, before reaching a strong bearing sand layer at MSL-40m, which was concluded after consulting boring logs. The barrier shall affect the Bay's hydrodynamics slightly in regular conditions. A decrease in flow area (constriction) at Bolivar Roads affects the tidal range and tidal prism of the Bay, influencing the water circulation in the bay and thereby the ecosystem. If the flow opening in Bolivar Roads becomes less than 60% of the original the Bay's ecosystem is adversely affected (Ruijs, 2011). In the conceptual design an opening of about 70% is aimed for. The storm surge barrier shall be designed to protect against surge levels with a return period of 1/10,000 yr^{-1}. Based on a preliminary cost benefit model, it is found that this protection level gives the highest rate of return (Stoeten, 2013). The structure is designed for a 200 year lifetime; comparable to the Eastern Scheldt Barrier in the Netherlands and the IHNC Lake Borgne Barrier in New Orleans.

BARRIER DESIGN Due to the large size of the Galveston Bay, there is an opportunity to construct a barrier that is only partly blocking the surge, leading to cost savings. Several options have been considered, such as only partly constructing a barrier over the length of the Bolivar Roads (called a reduction barrier), allowing flow under the gates (with a 'hinge gate') and overflowing by lowering the crest. For the conceptual design the final option (lowering the crest) has been chosen, as this seemed to provide the least technical difficulties and the lowest costs.

Navigational section

To accommodate shipping through the Bolivar roads a width of 220 meters, a depth of 17 meters and unlimited headway is required. The most suitable gate types for the storm surge barrier with the large span in the navigation section are a barge gate (see fig. 5, left) and a sector gate, which was applied for the Maeslant barrier) (see fig. 5, right). The barge gate has been selected as the best choice using a MCA. It is suitable for the wide openings, provides unlimited air draft, has reasonable construction and maintenance costs and does not transfer too much loads to the foundations.

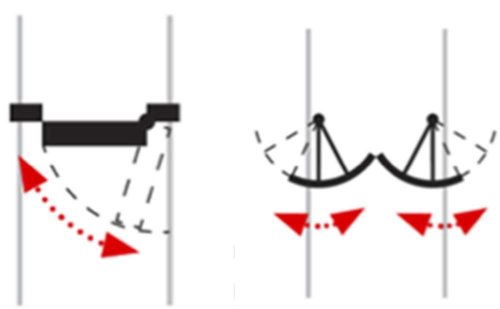

Figure 3: Barge gate (left) and sector gate (right)

A major disadvantage of applying sector gates to this case is that they cannot easily deal with negative hydraulic heads. A floating barge gate is a more suitable solution for negative heads, as it would simply 're-open' without any significant damage. The closure procedure of a barge gate is less complex as only one gate has to be closed compared to two in a sector gate system. Furthermore, the hinge required for a barge gate is less complex then for a sector gate. The hinges of the sector gates have to transfer the maximum load to the foundation, whereas loads for the barge gate are partly distributed to embankments (see below). Finally the space the barge gate occupies during recess / normal conditions is much smaller than for a sector gate. Therefore a barge gate is preferred for this application, see figure 3.

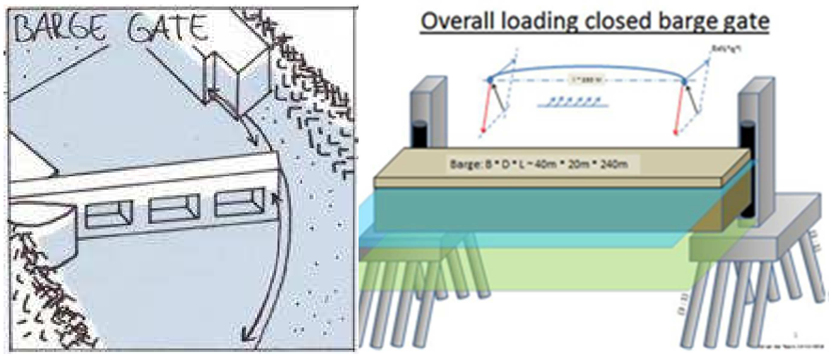

Figure 4: Impression of the barge gate (left) and proposed gate in the next phase of the study (right) (Jonkman et al., 2013).

A conceptual engineering design of the gate has been made (fig. 3 right). The barge gate in the Bolivar roads ('a' in fig. 6 right) will distribute the horizontal forces towards the embankments on the side of the ship channel ('b'). The barge gate contains valves within the main gate for stability during closure. Because of the poor soil conditions in combination with the underwater working conditions a deep pile foundation ('c') or a deep foundation realized by (pneumatic) caissons or cellular cofferdams are possibilities for the foundation of the barrier. The proposed barge gate can consists of a steel or (pre-stressed) concrete structure. Together with IV Infra and Royal HaskoningDHV preliminary engineering was done of the steel barge gate. The concrete structure was investigated by (Karimi, 2013). An alternative material to concrete and steel was investigated by M. van Breukelen, who looked at inflatables as storm surge barriers (van Breukelen, 2013).

Karimi expected, in his MSc Thesis, that the navigational barrier with the HLPC barge gate costs 303 million USD while a steel gate costs 538 million USD. Also, the maintenance costs of the concrete option are cheaper which makes the concrete barge gate a more economical option compared to the steel gate. Also, the total cost of the barrier of the Bolivar Roads Pass (including the environmental barrier and the navigation barrier) is estimated in the range of 2.3 billion USD to 4 billion USD(Karimi, 2013).

Bed protection is needed under the gate because of the high flow velocity and the large scour depth. Gate berthing system has been designed using wheel fenders. This fender type absorbs the berthing energy of the gate when it wants to rest on the abutments during the closure and provides free vertical movement of the gate during immersion at final location. The articulation system (swing point) has been proposed to be a ball-joint system or steel swing arms. On the basis of the system design of the barrier, the articulation system should provide free degrees of freedom in all the directions except surge and sway.

Environmental section
In an initial design a shallow-founded caisson barrier with vertical doors appeared to be the most appropriate barrier type for the environmental section (de Vries, 2014). In total, the environmental section included 338 gates each spanning 6.7 meters. The sill depth follows the present bottom profile and is MSL – 9.7m on average. The choice for caissons was based on their ability to spread the loads over the soil. However, during the design process it was concluded that the settlement of the clay layers underneath the caissons is too large. Given the foundation issues, other alternatives for the environmental barrier should be investigated.

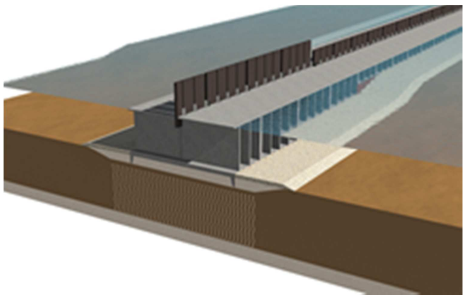

Figure 5: Birds eye sectional view of caisson barrier with vertical drain soil improvement (de Vries, 2014).

REMAINING WORK Remaining work on the storm surge barrier include more advanced physical and probabilistic hydraulic modelling to determine the hydraulic head over the barrier. The cost effectiveness of different retaining heights of the surge barrier could be investigated in terms of (barrier) cost savings versus additional flooding and costs in the bay. Further engineering of the barge gate is required regarding the foundation, scour protection, hinge, wave impacts, dynamic stability etc. Alternative barrier concepts for the environmental section need to be investigated, taking poor soil conditions in to account. Several of these subjects are being investigated in student projects at the University of Technology in Delft. An overview of all studies is given in the following table:

Component	**Author**	**Content**
Probabilistic surge suppression model for Galveston bay	Stoeten (2013) – MSc Thesis	Probabilistic model for estimating the response in a semi enclosed bay to hurricane surge forcing.
Storm surge barrier - Barge gate design	TU Delft/ RHDHV / IV Infra. (2013)	Sketch design of a steel barge gate in the navigational section of the barrier in Bolivar Roads, further engineering required.
Storm surge barrier – Environmental section barrier design	De Vries (2012) – MSc thesis	Design of the barrier in the environmental section. A caisson design was proposed, but the foundation proved to be difficult. Research in new alternatives is required.
Storm surge barrier – Navigation opening	Karimi (2013) – MSc thesis	Barge gate design in concrete. The HPLC material is selected as the appropriate material for design of the barge gate. This

w/ barge gate		material is environmentally friendly, durable and a reliable choice for the construction of a complex system such as the current barge gate. Permeability, strength and light weight are the other advantages of the HPLC.
Storm surge barrier – navigation opening w/ inflatable barrier	Van Breukelen – MSc thesis	Inflatable barrier alternative for navigational section of storm surge barrier.
Storm surge barrier – Barrier dynamics	Jor Smulders – MSc thesis	The dynamic respons of the barrier is investigated in this thesis. The main findings are that • During the swing operation the roll angle will be governing; • Barrier response increases slightly for increasing drafts; • Rubber supports is required to ensure barge is not damaged at landing; • Some self-excitation may occur in closed position.; • Additional measures are required in case of negative head.
Land barrier	TU MSc project group	Sketch design of land barriers on Galveston island.
Building with Nature options within the Bay	De Boer – MSc thesis (ongoing 2014/2015)	Investigation of building with nature solutions for surge suppression in the Galveston bay
Optimisation of barrier retaining height	Rippi – MSc internship (ongoing 2014)	Optimization of barrier retaining height in terms of barrier cost versus risk reduction.

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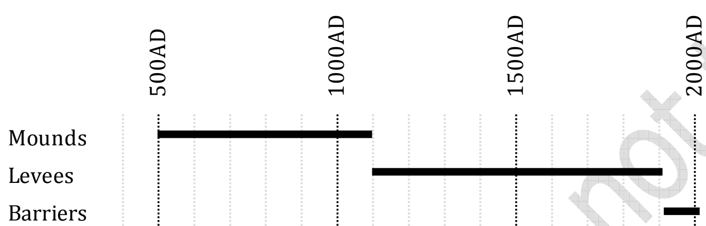
2) HISTORY OF COASTAL BARRIERS IN THE NETHERLANDS (RHDHV, L. Mooyaart)

1. Introduction

From many centuries the Netherlands have relied on some type coastal protection to survive (see Table 1). From 500 AD, this coastal protection consisted of man-made hills, so-called mounds. While the low lands were used for cultivation of crop and cattle, the mounds offered shelter during high (storm) tides. With further development of the Netherlands, these mounds proved to be inefficient[1] and unsafe though. Heightened roads between villages, called dykes, proved to require less soil, while providing protection to large pieces of land. These dykes (levees) remained the preferred strategy against coastal floods for many centuries. And for most locations in the Netherlands they still are. However, in 1916 it was decided to construct the first coastal barrier. Currently, six of the seven Dutch estuaries are equipped with a coastal barrier.

Table 1: Preferred coastal defense strategy in the Netherlands



This textbox describes these coastal barrier plans. This short history focuses on the main objectives of these plans, the alternative strategies considered and the main aspects assessed for the policy decision, as these are most relevant in this stage of planning a coastal barrier in the Houston-Galveston area. The following coastal barrier plans are discussed in this textbox: Southern Sea Works, Delta Works, Eastern Scheldt barrier and the Maeslant barrier.

2. Southern Sea Works [1]

The first plans to close off the Southern Sea originated from 1840. The main objective of these plans was to reclaim fertile land for agriculture. A privately funded society, called the Southern Sea Society, investigated the feasibility of land reclamation in the Southern Sea in more detail. During a period of approximately ten years, this society delivered eight technical notes, elaborating on the technical aspects of their plan.

Their plan consisted of four polders in the shallowest and clayey parts of the Southern Sea with a total size of approximately 200,000 hectares. The deepest and sandy part became a fresh water lake. This lake provided fresh water storage for both the new land reclamation and the existing land surrounding the Southern Sea. This fresh water lake was created by a coastal barrier, called the 'Afsluitdijk' (English: Closing dike), which prevented salt sea water

[1] It is actually estimated that 10 times more soil was applied to construct these mounds than was applied for the Pyramids in Egypt (Waterwolven).

to enter the lake. Furthermore the coastal barrier protected the inner area against coastal floods. The plan, however, had a negative impact on some existing activities as well. The existing fishing industry was harmed as salt water was obstructed. Furthermore, only two locks were available for commercial shipping and military defense.

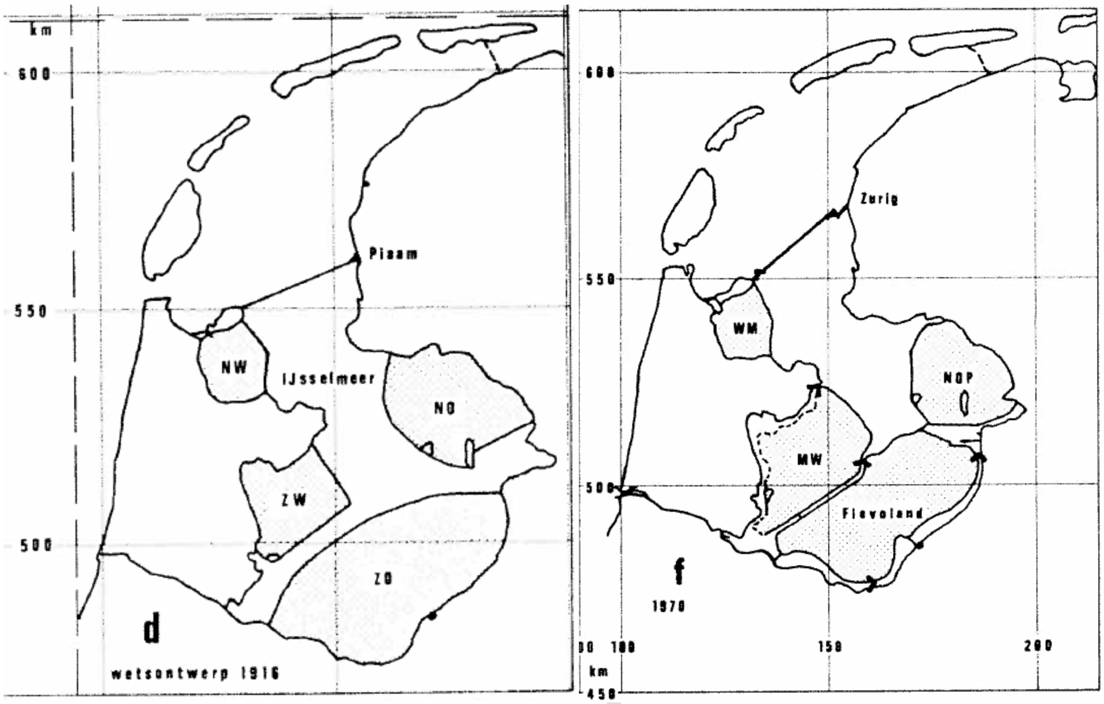


Figure 1: Final design of Southern Sea Works (right) and design according to Act in 1916 (left)

These aspects were investigated in detail and an economic study was performed weighing the costs and the benefits. Although the economic study gave a positive result, a political decision to construct the plan took several decades, as both the technical feasibility and the costs and the benefits according to the economic study were doubted.

Only after a coastal disaster in 1916, an act passed supporting the plan for the Southern Sea Works. After thorough preparation, construction of the coastal barrier began in 1926 and took eight years. Land reclamation of the first three polders followed in the decades hereafter, finishing in 1968. Both due to environmental objection and reduced economic feasibility of agriculture, the fourth and final polder was never constructed.

3. Delta Works

After the disastrous flood of 1953 in the South-Western part of the Netherlands, the Delta Committee was appointed by the Dutch government to prevent future coastal floods in this area. The plan they derived consisted of eleven coastal barriers partitioning and closing off the estuaries. Only the most southern estuary (Western Scheldt) and New Waterway had to remain open to allow navigation to Antwerp and Rotterdam, respectively. These sea entrances had to be protected by raising dikes along their waterway. The main aim of the

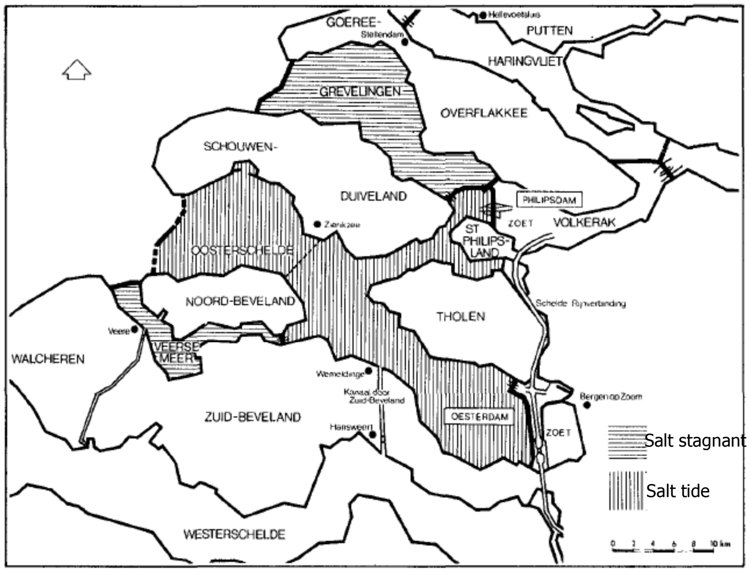
Delta plan was to protect the South-Western part of the Netherlands. Next to coastal protection, however, this plan provided fresh water, similar to the Southern Sea Works.

Figure 2: Delta Works [2]

4. Eastern Scheldt barrier [3]

During the construction of the Delta Works, public opinion changed. Altering sea arms into fresh water lakes became less popular. The Grevelingen Lake was still closed as planned, but remained salt due to a small sluice in the closure dam. A similar plan was adopted for the Eastern Scheldt and construction of the closed barrier started in the early 1970s, as planned. Only after massive protest by local fishermen and environment organizations, construction of the barrier was stopped.

From 1974 to 1976, three alternatives were extensively analyzed: a storm surge barrier, a closed barrier and an open estuary. With a storm surge barrier the tide in the Eastern Scheldt was constricted by narrowing the tidal opening during normal conditions. The tidal range in the Eastern Scheldt remained significant though (2.7 meters, which is 75% of original tidal range). The closed barrier alternative consisted of two barriers, creating one salt water lake without a tide and one fresh water lake. The opened barrier required dike strengthening along the Eastern Scheldt, but would only limitedly affect the existing water management regime. Figure 3 presents the proposed water management for these three alternatives.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OOSTERSCHELDE
NOORD-BEVELAND
THOLEN
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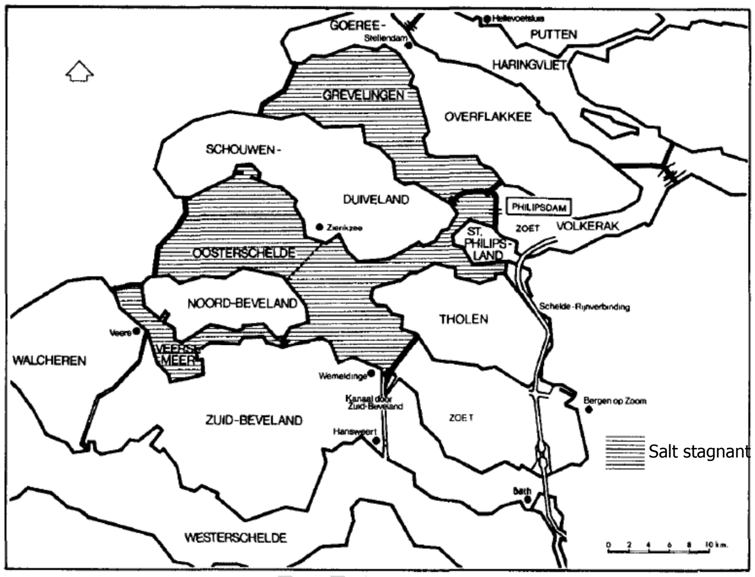
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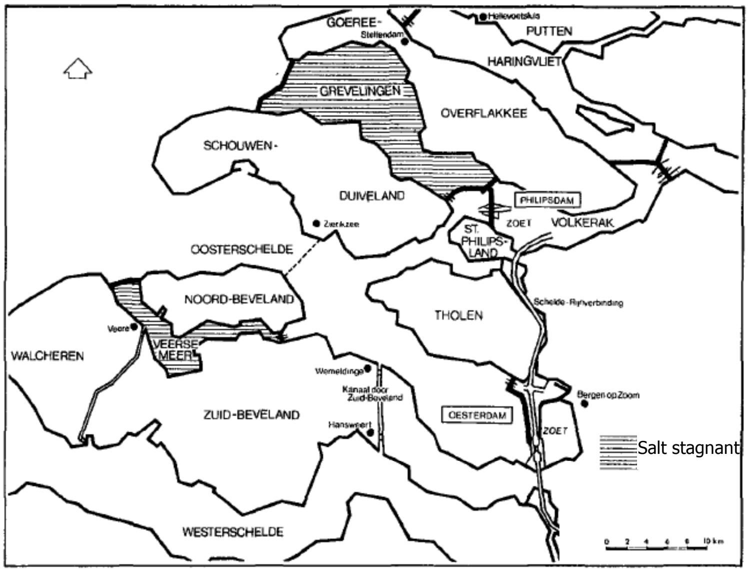

Figure 3: Three alternatives considered (upper: storm surge barrier, middle: closed, lower: open) [4]

Nine main aspects were studied for these alternatives to substantiate a policy decision: safety against floods, environment, commercial fishery, water management, inland shipping, recreation, costs and procedures, and employment. If possible, these main aspects were quantified. For example, the effect of these alternatives on the amount of phyto-plankton, mussels, fish and marine birds was estimated. The analysis resulted in a so-called score-chart, summarizing the influence of the three alternatives on each aspect. Table 2 is a summarized version of this score-chart

Table 2: Summary of score-chart

Aspect	Storm surge barrier	Closed barrier	Open estuary
Safety	+ Short coastal defence (9km) + High-quality solution +/- Construction period (11y)	+ Short coastal defence (9km) + High-quality solution + Short construction period (6y)	- Long coastal defence (145km) - Low-quality solution - Long construction period (20y)
Environment	+	-	+
Commercial fisheries	+/- Small impact	- Large impact	+ No impact
Water management	- Impact on adjacent fresh water lakes	+ No impact on adjacent fresh water lakes	- Impact on adjacent fresh water lakes
Inland shipping	Similar effect	Similar effect	Similar effect
Recreation	0	+ Expected increase	0
Procedures	+ In accordance with Delta act	+ In accordance with Delta act	- Not in accordance with Delta act
Costs (total costs in million guilders)	4,635	2,135	3,620
Employment (man/year)	34,600	15,500	23,500

Based on the before-mentioned policy analysis, the Dutch government decided to construct the storm surge barrier alternative.

5. Maeslant barrier [5]

Initially, it was intended to strengthen the levees near Rotterdam and Dordrecht to protect these cities against coastal floods. In the 1980s, however, levee strengthening proved to be very difficult, due to housing in and near levees. Furthermore, some recently strengthened levees required new strengthening to provide sufficient safety. To avoid this costly way of protecting against floods, the Dutch government studied the possibility of a storm surge barrier in the New Waterway.

As technical feasibility of a storm surge barrier was doubted, a contest between contractors was held. Five contractors were selected which were invited to submit designs and budgets. The first of October in 1987, only three months after the contest was initiated, six designs were received (see Figure 4)[2]. After technical feasibility became evident, this option was studied further. The year 1988 was used to draw up the environmental impact assessment (EIA) and to develop some of the designs in more detail (Rijkswaterstaat, 2014). The study showed that constructing a storm surge barrier had many advantages: the costs were lower and more accurate; the construction period was shorter and more certain; the length of the primary coastal defence was shorter, and the impact on environment and culture was limited. Table 3 presents the main results of the EIA.

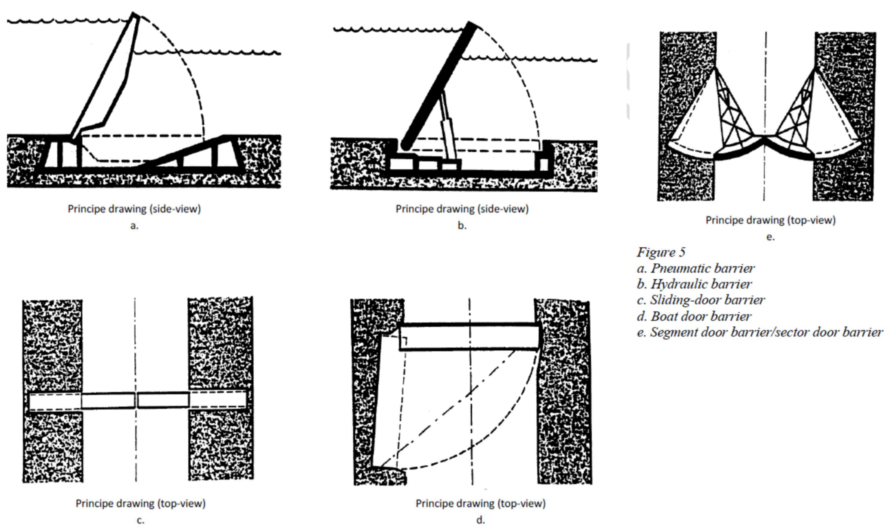

Figure 4: Maeslant barrier designs proposed by contractors

Table 3: Results EIA [6]

Aspect	Storm surge barrier	Dike reinforcement
Total costs	1.45 billion	1.8 billion
Accuracy costs	+/- 10%	+/- 20%
Delta safety	1996	2020
Accuracy construction time	2 years	10 years
Length coastal defence	35 km	300 km
Environmental and cultural damage	Limited	Massive

[2] Two contractors had a segment gate design.

Based on the EIA, the Dutch Government chose to construct a storm surge barrier. The design with two floating sector doors prevailed, as maintenance of this option is relatively easy[3]. The barrier was constructed between 1989 and 1997. Although the barrier is closed yearly for testing, there has been only one closure required to prevent flooding during its operation.

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4. Rijkswaterstaat, 1986, Design documents Eastern Scheldt barrier
5. Rijkswaterstaat, *no date*, basic documentation Maeslant barrier, version 4.0
6. Land+Water, special '96

[3] The barge gate was not chosen as the design was not worked out in sufficient detail. Therefore, this could have been a feasible option for the Maeslant as well.

3) SUMMARY OF 'TEXAS COAST HURRICANE STUDY' REPORT OF USACE, DATED 1979 (TU Delft, Lendering)

The primary objectives of this comprehensive investigation have been to develop and compile information on the characteristics and frequencies of hurricanes which affect the Texas coast, to identify ways of reducing losses from hurricane flooding, and to determine the feasibility of constructing protective measures for long reaches of the coast. Studies for both comprehensive and localized plans for providing hurricane flood protection for the Texas coast have been performed.

Comprehensive plans were developed and evaluated for the Galveston Bay, Matagorda Bay, and Corpus Christi Bay study segments. The length of protection indicates the total length of earthen levees, seawall, and floodwalls for the primary and supplemental systems. Also shown in the tables are the land areas protected, the estimated total construction costs, and the corresponding benefit-cost ratios for the combined primary and supplemental systems.

TABLE 6

COMPARISON OF COASTAL BARRIER PLANS

	Length of Protection (Miles)	Area Protected (Acres)	Total Construction Costs (Millions)	Benefit-Cost Ratio
Galveston Bay	85	316,000	$ 1,494	1.1
Matagorda Bay	100	448,000	359	0.2
Corpus Christi Bay	145	96,000	950	0.4

TABLE 7

COMPARISON OF ALTERNATE BARRIER PLANS

	Length of Protection (Miles)	Area Protected (Acres)	Total Construction Costs (Millions)	Benefit-Cost Ratio
Galveston Bay	71	282,100	$ 1,231	1.2
Matagorda Bay	128	432,000	280	0.3
Corpus Christi Bay	88	50,000	600	0.5

As was indicated in the preceding discussion, localized plans were evaluated in each of the five study segments. Table 9, shows the various localized plans evaluated for the Galveston bay area, length of protection system, area protected, total construction costs, and benefit-cost ratio. More than one plan was evaluated for several of the cities; however, only the best plan from an economic standpoint is presented:

TABLE 9

SUMMARY OF LOCALIZED PLANS

	Length of Protection (Miles)	Area Protected (Acres)	Total Construction Costs (Millions)	Benefit-Cost Ratio
Galveston Bay Area				
Angleton	24	65,000	$ 70	0.7
Baytown	15	11,400	119	0.5
Galveston	13	8,000	94	2.4
La Marque-Hitchcock	8	6,100	37	0.4

The studies conducted show that large areas along the Texas coast are vulnerable to hurricane flooding. These areas include extensive industrial developments, some of which are critical to the economic well-being of the country, and millions of people, many of which are unaware of the hazards associated with hurricanes. Several comprehensive and localized structural plans to protect these areas along the Texas coast were found to be economically feasible, but none of these plans were supported by a local sponsoring agency and the local citizenry. It has, therefore, been concluded that implementation of the protection plans should not be undertaken at this time. In the absence of structural protection measures, there is tremendous opportunity for the various political entities to regulate future development of the areas subject to hurricane flooding in such a way as to be consistent with damage potential for each area.

4) CONCEPTUAL DESIGN AND PHYSICAL MODEL TESTING OF THE LAND BARRIER SECTION FOR THE GREATER HOUSTON METROPOLITAN AREA STORM SURGE SUPRESSION System (TAMUG, Figlus)

Keywords: Physical modeling, conceptual levee design, core-enhanced sand dunes, dune and levee erosion, hurricane surge impact

Background: The "Ike Dike" is a proposed barrier concept providing coastal protection against damage from hurricane storm surge to the Greater Houston Metropolitan Area. In 2008 the waves and storm surge produced from Hurricane Ike alone destroyed 60% of homes in affected coastal communities with an estimated property damage cost of $5 billion ($25 billion total) with the main problem being the fact that the storm surge was able to enter Galveston Bay where hurricane winds continued to amplify its damaging effect. Twenty lives were lost and Hurricane Ike was still far from the worst case scenario which would have even more dramatic implications for the local, state, and national economy. The protective barrier being developed in this project is envisioned as a 100-km long coastal spine along Galveston Island and the Bolivar Peninsula. Its intent is to limit the damaging effects caused from storm surge entering the Galveston Bay by blocking a portion of the surge at the coast. Three major conceptual sections make up the entire coastal spine: (1) the existing Galveston seawall, (2) mechanical gates across the inlets to Galveston Bay, and (3) a coastal land barrier (levee) for the remaining stretch of the coastal spine. More detailed information on the findings presented in this summary are given by West (2014).

Objective: The objective of this study is to come up with a conceptual engineering design for the 83-km long land barrier portion of the coastal spine including general cross-section dimensions and required material and cost estimates. In addition to providing adequate storm surge protection, the land barrier has to be integrated into the landscape, socio-economic, and environmental fabric of the existing coastline in a beneficial and aesthetically pleasing way. The levee-in-dune (LID) concept investigated in this study seems to be best suited to comply with these design restraints. A LID is a hybrid coastal barrier made up of a protective levee structure hidden inside a coastal sand dune. The specific research goals for this study are:

1. Develop basic conceptual design of the land barrier cross-section based on a 100-year return period level of protection (i.e. crest elevation and side slope).
2. Perform physical model tests in a moveable-bed wave flume comparing LID hydrodynamic and morphodynamic behavior under storm wave attack for various core alternatives (sand core, armor stone revetment, clay core, and concrete T-wall) to identify the most beneficial option.
3. Perform numerical model analysis of the LID hydrodynamic and morphodynamic behavior under hurricane conditions to identify the most beneficial option.

Approach: The conceptual cross-section design of the LID is based on requirements and recommendations for levee design and construction detailed in the US Army Corps of Engineers Coastal Engineering Manual (USACE, 2000). Cost estimates are based on literature reported values of comparable completed levee construction projects. The physical model tests comparing various LID core alternatives have been carried out using TAMUG's 15-m long moveable-bed wave flume under irregular wave attack and high water level with the intent to simulate 100-year return period peak storm conditions. Hydrodynamics were measured using nine capacitance wave gauges positioned strategically along the flume. Profile evolution was recorded at set intervals between wave bursts via a laser line scanner system to detect erosion and deposition patterns for each LID alternative. The LID alternatives considered in this study include a homogeneous sand dune (no core) and three dunes, each incorporating different protective cores: an armorstone revetment core, a clay levee core, and a concrete T-Wall core.

The numerical morphology models CShore and/or XBeach will be used to analyze the morphodynamic evolution of the different LID alternatives under hurricane surge and wave conditions. The input for these models will be provided by ADCIRC surge model runs using a series of synthetic hurricanes.

Results: Figures 1 – 4 show the prototype dimensions of the four considered LID concept alternatives to be placed on the open beach along the Galveston and Bolivar coastlines. The evaluation of different LID design alternatives revealed advantages and disadvantages of each alternative. The No-Core LID is the simplest of the four alternatives. The design requires only sand, which can be dredged from offshore or taken from local quarries. This also means that the No-Core LID would be the simplest to construct which reduces cost. However, the No-Core LID has no protective core, meaning that its only defense against storm surge is reliant solely upon the amount of material in the dune. This, combined with the threat of seepage through the high porosity sand requires the design to have a much larger footprint than concepts with less permeable cores. Reinforcing the dune with an armorstone layer (the Armorstone-Core concept) can protect the dune from scarping, however will not prevent seepage through the dune. This means that even though the dune is reinforced, its width cannot be reduced. The Clay-Core LID offers reinforcement similar to the Armorstone-Core LID, with the added benefit of preventing seepage, since clay has very low permeability. This allows the LID to be significantly narrower than an LID with a sand core. However since the Clay-Core LID is still considered a soft structure, it still runs the risk of erosion, and subsequent failure. The T-Wall LID has substantial design flexibility over the other LID concepts. Since the T-Wall itself has a very small footprint, it is possible to greatly reduce the width of the dune itself, which would in turn reduce costs and space requirements. A summary of the different LID concept geometries, required material volumes and costs is provided in Table 1.

The physical model wave flume tests revealed interesting differences in the erosion patterns of the four LID alternatives, all of which started with the same initial profile and were subjected to the same wave forcing. While all alternatives showed significant erosion under wave attack and elevated water levels, the final measured profiles varied substantially (Figure 5). All LID core alternatives reduced the retreat of the eroding dune scarp compared to the No-Core-LID but the respective effect on dune erosion differed among alternatives. The armorstone revetment reduced dune erosion but still allowed for some sand to be washed out from underneath the revetment resulting in settlement of the armorstone layers. This could be prevented via graded filter layers. The sand covering the clay core eroded most rapidly but the clay core itself withstood all wave attack in the model setting leading to the least eroded LID volume. The T-wall core led to the largest LID erosion volume even though the vertical wall completely stopped the progress of the eroding dune scarp. This is mainly due to scouring mechanisms at the toe of the wall and would need to be alleviated through toe scour protection in a prototype.

Both the conceptual LID designs and the physical model tests represent a first attempt to come up with a viable design for the land barrier section of the "Ike Dike" but further studies are necessary to refine these concepts further.

Remaining Questions/Steps: Numerical modeling of the morphodynamic evolution of the different LID alternatives is very complex and is currently still work in progress. In addition, current LID design considerations are rather conservative since they do not account for the beneficial effects afforded by the sacrificial LID sand cover and do not consider the potential to allow overtopping of the structure. Further numerical and physical model investigations are necessary to optimize the LID design by including overtopping and the effect of the sand dune cover in reducing wave and surge impact.

Interaction with Other Sub-Projects: The LID conceptual design considerations provide input for the study related to the integration of the surge protection infrastructure and resilient community development as well as the economic cost-benefit analysis related to the entire "Ike Dike" concept. The numerical morphodynamic modeling component of this study builds on input from the sub-project dealing with ADCIRC hurricane storm surge modeling.

Key References:

- West, N.A. (2014). "Conceptual Design and Physical Model Tests of a Levee-in-Dune Hurricane Barrier." M.Sc. Thesis Ocean Engineering, Texas A&M University.
- U.S. Army Corps of Engineers. Engineering Manual 1110-2-1913, Design and Construction of Levees. Technical Report March 1978, US Army Corps of Engineers, Washington DC, 2000.

Figures/Tables:

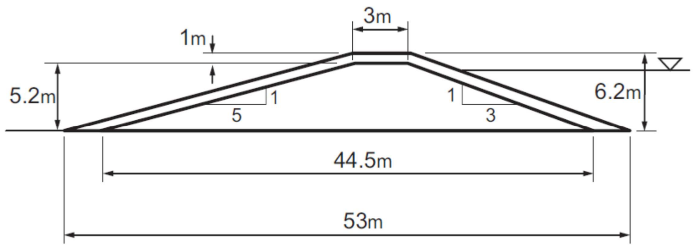


Figure 1. Schematic of the cross-section for the LID concept without special core (sand dune only).

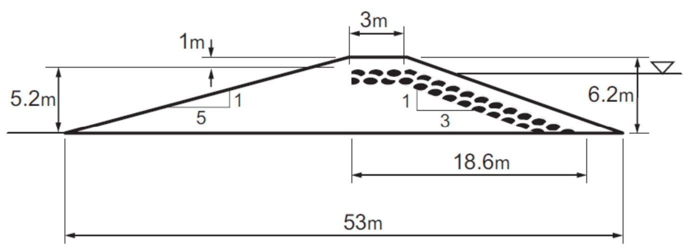


Figure 2. Schematic of the cross-section for the LID concept with armor stone revetment core.

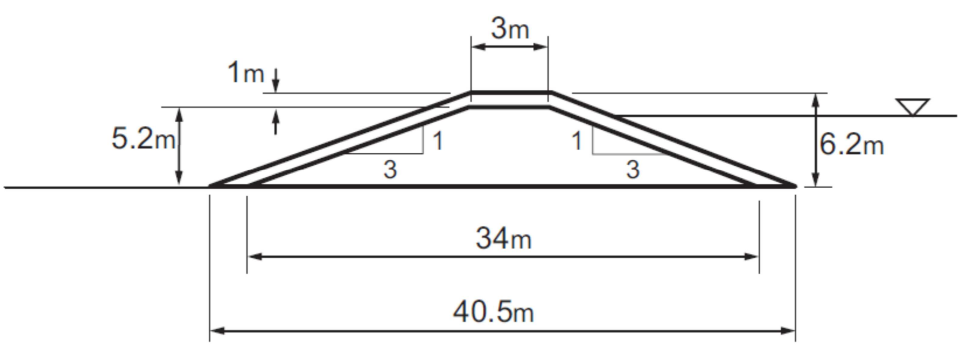


Figure 3. Schematic of the cross-section for the LID concept with clay levee core.

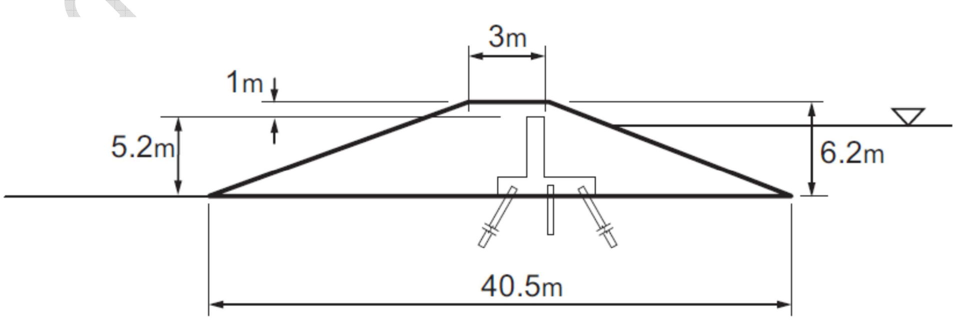


Figure 4. Schematic of the cross-section for the LID concept with concrete T-wall core.

Table 1: LID prototype geometry, material volume, and cost for all four considered conceptual design alternatives.

Concept	No Core	Armorstone	Clay	T-Wall
Height [m]	5.2	5.2	5.2	5.2
Sand Layer Thickness [m]	1.0	1.0	1.0	1.0
Crest Width [m]	3.0	3.0	3.0	3.0
Total Footprint Width [m]	53.0	53.0	40.5	40.5
Flood-Side Slope [-]	1v:3h	1v:3h	1v:3h	1v:3h
Land-Side Slope [-]	1v:5h	1v:5h	1v:3h	1v:3h
Sand Volume [m^3/m]	174.3	158.9	39.2	130.8
Core Volume [m^3/m]	-	15.3	96.3	4.7
Total Volume [yd^3/yd]	174.3	174.3	135.5	135.5
Cost [$M/mi]	5.7-6.1	6.1-11.5	3.4-5.7	33.6

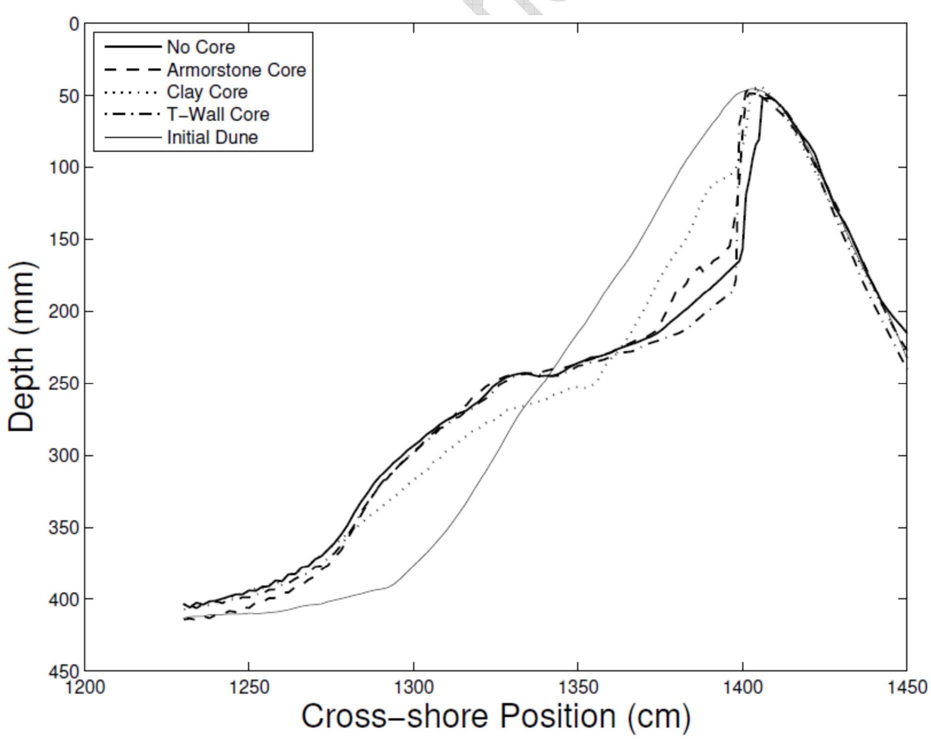


Figure 5. Comparison of measured initial and final cross-shore profiles for each LID alternative from wave flume physical model experiments.

5) INTEGRATING SURGE PROTECTION INFRASTRUCTURE AND RESILIENT COMMUNITY DEVELOPMENT (TAMUG, Galen Newman and Eric Bardenhagen)

Investigators: Galen Newman, Eric Bardenhagen

Keywords: Surge suppression; resiliency; landscape representation; coastal ecology; community development

Background Comprehensive storm surge protection infrastructure systems have proven effective in protecting coastal communities prone to hurricane storm surge and resultant flooding. Due to the size and required system contiguity, many systems have resulted in adverse ecological and cultural effects such as disturbances to water exchange, increased land cover conversion and habitat fragmentation while cultural disruptions include physical and visual coastal disconnection, decreased beach area and challenges to commercial and tourism activities tied to coastal environments. This research evaluates both structural and non-structural mechanisms for ecologically and culturally integrating the proposed storm surge protection infrastructure comprising the Ike Dike. These mechanisms are then applied into a large-scale multifunctional framework using four targeted environments in western Galveston Island, TX as test sites.

Objectives While the protection of populations is the primary goal of the coastal spine, integration of the infrastructure into the landscape is a key objective. This research also seeks to generate a framework for developing a comprehensive storm protection system for the Houston-Galveston MSA which preserves or enhances ecological processes and cultural practices into an integrated system. Multifunctional strategies and program options are being established to achieve this integration. The purpose is to generate research that will serve as the basis for a visual landscape plan. This plan will identify ways to integrate the proposed Ike Dike infrastructure elements that are socially, economically, and ecologically sound. The plan seeks to:

1. Develop a regional framework for development to occur in Galveston which clearly identifies risk areas, areas prime for ecological reclamation, future population centers, and existing natural, cultural and recreational resources.

2. Conceptualize a master plan for the protective dune which projects it as a multifunctional linear armature which protects populations, spurs new development, and connects people to coastal areas.

3. Utilize innovative digital representation techniques to visualize existing and proposed data and designs for public presentations

Approach The study is aimed at providing various design solutions and to integrate the landscape into what is typically monolithic storm surge infrastructure. Dune systems can effectively prevent storm surges and mitigate flood issues but can also socially and socially segregate valuable sea front areas, decrease connectivity and walkability, and fragment habitat areas. Initially, evidence is drawn from case study comparisons of related efforts in the Netherlands and New Orleans. Social, economic, and ecological impacts of these mechanisms are compared across these cases and used to inform integration options. Next, a development potential framework is developed using Geographic Information Systems (GIS) suitability modeling and weighted overlay techniques for Western Galveston and targeting four representative coastal sites integration option exploration: a Coastal Tourism Area, an Area in Transition toward development, an existing Urbanized Area and a Minimal Impact Area within a State Park.

Results The creation of an integrated coastal spine within the region provides a unique opportunity to create resilient communities while also providing multiple cultural and ecosystem services to its residents. Early results indicate that the surge infrastructure could be implemented with relatively minimal impact on connectivity and natural processes while increasing development opportunities. Differing design elements have their own features and effects in terms of flexibility, natural values, multi-functionality, accessibility and seafront relation in each environment. Various design elements should be chosen prudently to address specific on-site issues, to fulfill different requirements, and to maximize the benefits economically and ecologically. The strategic use of appropriate surge protection mechanisms and integration with ecological processes to mediate water exchange, strategically utilize excess sedimentation, and afford the reclamation of lost habitat will further enhance the Ike Dike's ability to cultivate ecological integration while generating resilient communities. Primary issues for integration include 1.) after the surge protection infrastructure is implemented, it could cause several environmental changes, affecting existing sensitive habitats, sea grass, and oyster reefs. 2) If not implemented effectively, the dune system may block the visual connections between existing houses and the sea, 3) dune implementation must be carefully placed due to narrowing beach widths toward the eastern side of the island and new sediment may be necessary, 4) placement of the dune may need to "snake" within existing and future development areas, and 5) coastal areas are frequently encroached by seaweed deposits which require reuse strategies.

Remaining Work Future research will concentrate on 1) developing growth plans for each of the four aforementioned target environments, 2) 3-D modeling of site master plans, 3) perspective and section renderings of integration options utilized in each target environment, and 4) a fly-through video showing the implemented dune system integrated within the landscape.

Interactions with Sub-projects Newman, G. Brody, S. & Smith, A. (under review). 'Integral Resiliency: Regenerating Vacant Land through Ecological Connectivity with Geodesign.' *Landscape and Urban Planning*, special edition on Geodesign

Figures See next 2 pages as Appendixes

6) STORM SURGE MODELING FOR THE IKE DIKE STUDY (Jackson State, Thomas Richardson)

Jackson State University: Bruce Ebersole (PI), Tom Richardson, Robert Whalin, Don Hendon (graduate student), Chris Herron (graduate student), Nakarsha Bester (graduate student)

Engineer Research and Development Center (ERDC): Chris Massey, Norberto Nadal, Jeff Melby

Background: Cooperative R&D Agreement with Engineer Research and Development Center signed 10 Sept 2012. Memorandum of Understanding with Texas A&M University at Galveston signed 14 December 2012. Initial funding from City of Galveston received 4 April 2013. Additional funding from Bay Area Coastal Protection Alliance received 2 July 2014.

Objectives: Deliver probabilistic hurricane surge inundation estimates to the Ike Dike economics team for use in a first-order economic impact analysis. Assess the effects on hurricane surge in Galveston Bay of varying Ike Dike characteristics such as crest elevation, locations of east and west termini, terminal tie-backs to higher land elevation, and barrier gate configurations.

Approach: The overall approach to this subproject has four components: 1) select a suite of storms, both historic and hypothetical, that represent the hurricane climatology of the Houston/Galveston area, 2) calculate the waves, combined surge and wave setup, and the resulting inundation that these storms would produce at the coast and in Galveston Bay for with-and-without-Ike-Dike conditions, 3) deliver outputs from component 2 to the economics team in formats suitable for making damage estimates, and 4) deliver outputs as needed to other teams, such as those working on concepts for the surge gate and land-based barrier. The work in all components will be executed in a manner compatible with: a) recently-completed flood risk mapping in the Houston/Galveston area by the Federal Emergency Management Administration (FEMA), and b) subsequent studies that may be performed by the U.S. Army Corps of Engineers or others.

Results (a/o 12 Nov 2014): Thus far, the waves and inundation from 26 storms have been calculated, using ERDC's Coastal Storm (CSTORM) modeling system and high-performance computing resource, for with-and-without-Ike-Dike conditions:

- Hurricane Ike, as occurred
- Twenty-one 900 mb storms from the suite used by FEMA, each on a different track covering the entire study area and somewhat beyond.
- Four storms from the suite used by FEMA, ranging from 975 to 900 mb, all on the same "direct hit" track making landfall over the city of Galveston

The "with-Ike-Dike" condition used to date is a single monolithic barrier with the same crest elevation as the existing Galveston seawall. As shown in Figure 1 below, it begins west of

Freeport, TX, and follows the coast northeast to a point approximately 20-25 km east of where the Bolivar Peninsula begins. It extends across all breaches, inlets, and entrances, including Bolivar Roads, and has no end structures connecting it to higher elevations inland.

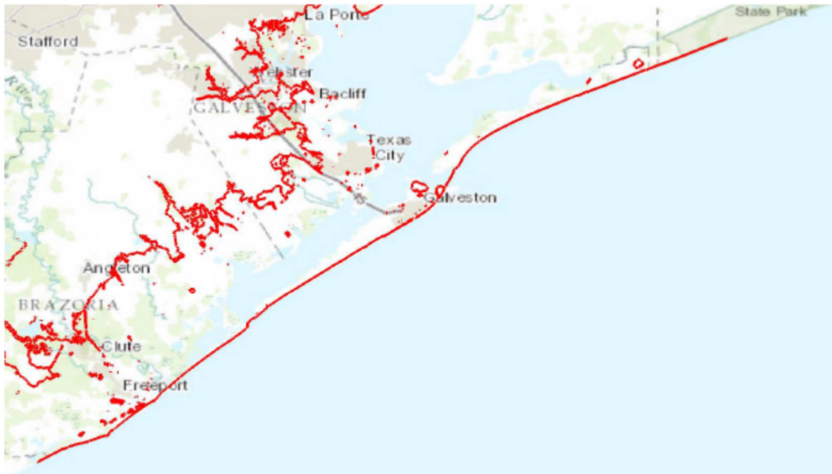


Figure 1. Current Ike Dike representation in CSTORM and approximate location of landward contours with same elevation.

Remaining Questions and Steps: The specific approach to this subproject has been to establish general upper bounds for the Houston/Galveston hurricane climatology and its resulting effects, then to investigate the sensitivity of inundation and resulting damages within Galveston Bay to variations in parameters such as storm intensity, track, landfall location, and size. The intent is not to produce an exhaustive analysis but rather to define reasonable limits within which the optimum design solution is likely to be found. How far and in what directions this specific approach will lead will be driven to a large degree by results from the economics team and by the need to demonstrate the economic value of a hurricane barrier to potential funding sources and to the general public. To this end, a separate product, "Feasibility Study of the Ike Dike Concept – Flood Risk Reduction", is intended to be a living document that tracks the evolution and ongoing results from this specific approach. It contains recommendations for next steps and the rationale behind them.

Interactions with Other Subprojects: Results from all simulations conducted to date were provided to the economics team. Their initial analysis has focused on with-and-without-Ike-Dike damages from the four "direct-hit" storms plus damage verification using the Hurricane Ike "without" results. Wave energy spectra from Storm 128, a 900 mb event from the FEMA storm suite, were provided to Jor Smulders for use in assessing the dynamic behavior of a Bolivar Roads barge gate.

Key References:

- http://adcirc.org/files/2014/04/CSTORM_MS_ADCIRC_Mtg_2014_Chris_Massey.pdf
- "Feasibility Study of the Ike Dike Concept – Flood Risk Reduction", version dated 11/??/2014

7) ECONOMIC IMPACT OF HURRICANE SCENARIOS FOR THE GALVESTON BAY- A COMPARISON OF LOSSES WITH AND WITHOUT COASTAL BARRIER (TAMUG, Brody and colleagues)

Center for Texas Beaches and Shores (CTBS), Texas A & M University.
Center of Excellence, Analysis and Response for Coastal Hazards, Jackson State University

Report by Samuel Brody & Kayode Atoba

Keywords: Economic Loss; Ike Dike; Storm Surge; Coastal barrier

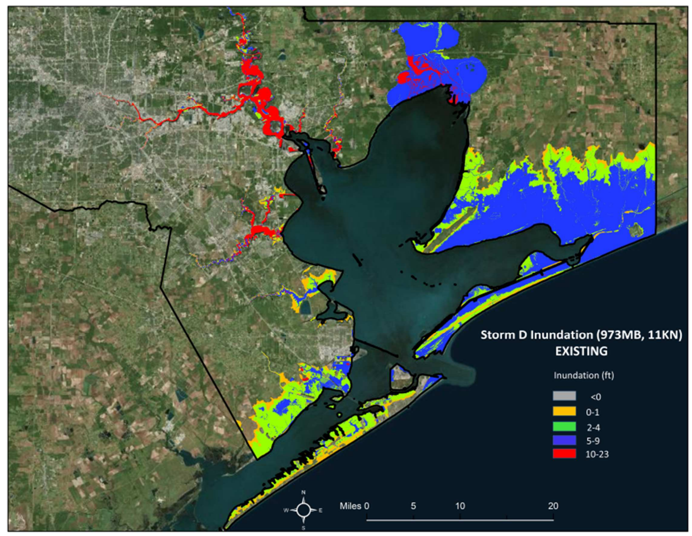


Figure 1: Inundation With Existing Coastal Conditions

Background

The effects of hurricane and storm surge events have been accompanied by significant economic losses. For example, hurricane Ike cost an estimated $25 billion in damages to buildings, contents, and indirect economic losses (Berg, 2009). As a result, the need to protect vulnerable coastal areas has ignited discussions on structural and non-structural storm surge mitigation strategies. This project examines the economic impact of probabilistic hurricanes that could directly hit the Galveston Bay area, and how the construction of a coastal barrier could reduce vulnerability and economic losses from possible storm surge events.

Objectives

Our main objective is to carry out a cost-benefit analysis of a coastal spine ("Ike Dike") in terms of potential reduction of flood losses. To achieve this objective, we begin by modelling surge damages with and without the construction of a dike, and the extension of existing seawalls. We then examine the differences between losses from different probabilistic hurricane scenarios on direct economic losses to buildings and contents, indirect economic losses, transportation losses, loss of use, and the overall economic impacts of such storm surge events. We also plan to identify the effect of the project on the regional economy.

Approach

We use the Federal Emergency Management Authority (FEMA) approach to estimate losses. The industry standard Multi-hazard Loss Estimation Methodology (HAZUS-MH) flood model has been used extensively by federal, state, and regional government including private enterprises to make critical decisions related to flood preparation and even vulnerability assessment. It has been found that using user-provided data rather than HAZUS default has significantly improved loss estimation result (Ding et al, 2008); hence we have used up-to-date parcel data for Harris and Galveston County to input building characteristics and enable a better mapping scheme for these structures rather than the HAZUS default. We have also used secondary analysis of storm surge rather than depend on the rudimentary SLOSH and SWAN models provided by HAZUS to determine flood vulnerability and inundation, making our HAZUS analysis a level 2-3 analysis which can be applied to prefeasibility engineering studies, Environmental Impact Analysis, and educational/research purposes (HAZUS-MH user manual).

Our study area includes Harris, Galveston, and Chambers counties where we collected parcel data from the appropriate county appraisal district, isolating the 2014 improvement data across all occupancy types, and replaced the default census data used in the HAZUS database. We then used a 3-meter resolution Digital Elevation Model (DEM) in addition to the maximum surge elevation provided by Jackson state University to model flood inundation. We used the parcel information to map flood schemes, where foundation type is available, and HAZUS methodology by building year of construction where foundation type is unavailable.

We modeled maximum surge elevation from an ADCIRC (ADvanced CIRCulation Model) run of a coupled Surge and Wave model, which considered local conditions of both primary and secondary protection levels around Galveston Bay (e.g. existing Texas City dike and Proposed Ike dike). A total of 50 hurricane scenarios were run in ADCIRC (25 with existing coastal conditions, and 25 for the Ike Dike). Four storms directly impacting Galveston Bay with different intensities were run for a preliminary report and loss estimation. The maximum surge elevations were computed and interpolated to generate inundation after analysis with the existing DEM of the study area. Losses were then computed from inundation scenarios based on Army Corp of Engineers (USACE) damage curves for different occupancy types to generate loss estimates for buildings.

Results

Our preliminary analysis shows significant reduction in losses. For example, for the largest of the four storms (Storm A), building loss without a coastal spine was approximately $3.73 billion. This economic impact was reduced to $1.17 billion with coastal protection in place. In fact, for the total predicted economic loss, we calculated a 68% reduction with the placement of a 17-foot dike along Galveston Island; scenario B saw an 80% reduction, storm C about 88%, and scenario D about 82% reduction in combined economic losses (see Table 1).

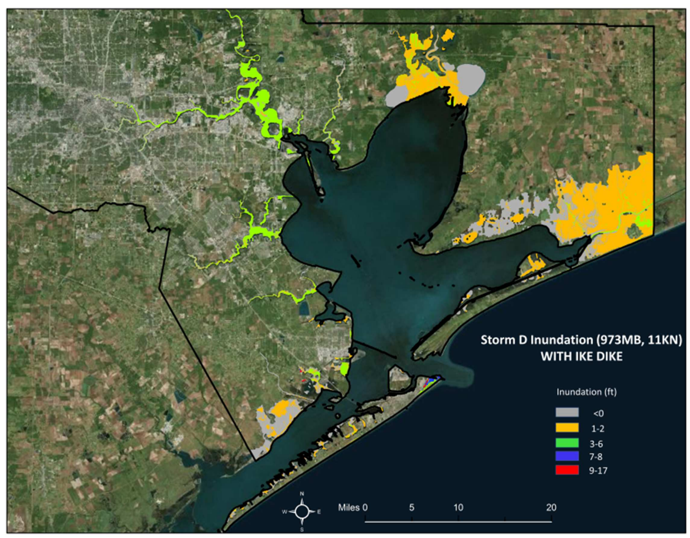


Figure 2: Inundation With Ike Dike and Seawall extensions

Future Work

We have encountered some limitations on the parcel data provided for industrial facilities, in most cases, some of the heavy industrial facilities and the many petrochemical complexes in the Port of Houston. Other parts of the study area are highly undervalued and the loss estimation for these facilities is underestimated. We are currently working with the University of Houston's Economics department to collect industry data for petrochemical complexes. We are also in the process of running more validation studies with hurricane Ike and improved storm probabilities for the study area. We also plan on examining losses at larger scales on specific areas, parcels and census blocks, especially on areas with high vulnerability.

Interactions

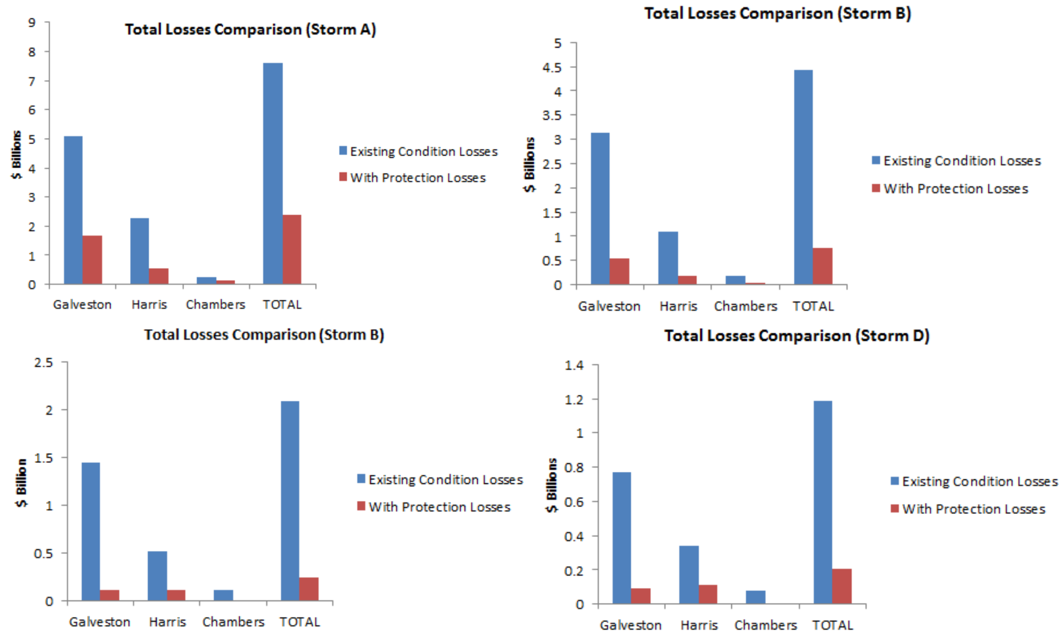
This project is part of a multifaceted attempt to improve resilience in the Galveston Bay area. A critical part of this research is that it informs us about the economic and physical improvement that can be achieved from structural mitigation. Research is also ongoing on the methods of predicting future developments in coastal areas, resident's perception of structural and non-structural mitigation, engineering design of structural barriers, and an aggregated resiliency research for the Galveston Bay. The linkage of this research with other ongoing research would enable us to effectively assess vulnerability, not just in the Galveston Bay, but ultimately for the Texas coast in the future.

Table 1: Estimated Losses with and without Coastal Spine

Storm A (900mb, 11kn)				
	Existing		**Protected**	
	Building* Loss	Combined Loss	Building Loss	Combined Loss
Galveston	2.53	5.10	0.85	1.68
Harris	1.08	2.26	0.25	0.56
Chambers	0.12	0.26	0.07	0.15
TOTAL	**3.73**	**7.62**	**1.17**	**2.39**
Storm B (930mb, 17kn)				
	Existing		**Protected**	
	Building Loss	Combined Loss	Building Loss	Combined Loss
Galveston	1.52	3.14	0.36	0.54
Harris	0.51	1.09	0.07	0.19
Chambers	0.08	0.19	0.01	0.03
TOTAL	**2.11**	**4.42**	**0.44**	**0.76**
Storm C (960mb, 11kn)				
	Existing		**Protected**	
	Building Loss	Combined Loss	Building Loss	Combined Loss
Galveston	0.69	1.45	0.06	0.12
Harris	0.24	0.52	0.05	0.12
Chambers	0.05	0.12	0.002	0.007
TOTAL	**0.98**	**2.09**	**0.112**	**0.247**
Storm D (975mb, 11kn)				
	Existing		**Protected**	
	Building Loss	Combined Loss	Building Loss	Combined Loss
Galveston	0.36	0.77	0.05	0.093
arris	0.14	0.34	0.04	0.111
Chambers	0.03	0.08	0.002	0.005
TOTAL	**0.53**	**1.19**	**0.092**	**0.209**

Table 1 showing building loss and combined economic loss comparison for the four storm scenarios

*All values are in $ Billions



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8) FLOOD RISK REDUCTION ANALYSIS FOR THE CLEAR CREEK WATERSHED (TAMUG, Brody and colleagues)

Sam Brody, Wes Highfield, Russell Blessing - Texas A&M University

Antonia Sebastian, Rice University

Key Words: Floodplain, Flood losses, Clear Creek, land use, mitigation.

This project involves a parcel level analysis of the Clear Creek watershed situated along the west coast of Galveston Bay, TX. Observation data and spatial analytical techniques were used to assess: 1) spatial hotspots of flood risk and impacts; 2) the influence of land use and development patterns on flood losses; and 3) the effect of mitigation strategies on reducing property damage from floods. Both wave and precipitation-based flood events were examined.

The Clear Creek watershed, located 20 miles south of Houston, Texas encompasses a 197 square-mile area covering the following four counties: Galveston, Brazoria, Harris and Fort Bend (Figure 1). The watershed is drained primarily by Clear Creek and associated tributaries. Clear Creek itself is a tidally influenced bayou that terminates as it enters Clear Lake, which then opens into west Galveston Bay. The Clear Creek watershed typifies the Gulf Coast physical environment, with very little topographic relief, large percentages of floodplain area, wide floodplain boundaries and exposure to frequent storm events. Over the study period, from 1999 to 2009, both multiple small-scale and major flooding impacted the Clear Creek Watershed. Overall, significant increases in residential development in vulnerable areas over the last decade have resulted in large amounts of property damage caused by repetitive flooding events. Over the 11-year study period, 9,792 NFIP-based flood damage claims (FEMA 2011) were mapped and analyzed across the Clear Creek watershed for a total of greater than US$356 million (in 2009 dollars), most of which stemmed from structural losses.

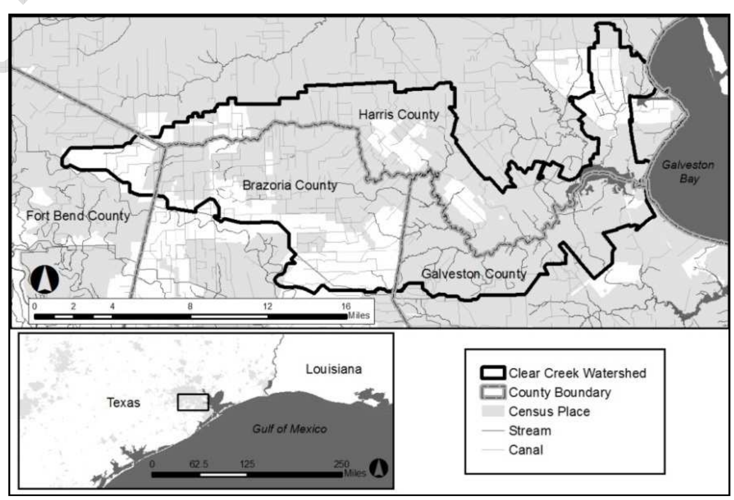

Figure 1: Clear Creek Watershed Study Area

Results from the comprehensive analysis include the following:

- Over 40% of insured flood losses and 55% of damage claims occurred outside of the 100-year floodplain. The average loss per claim across the watershed was US$36,585 (US$26,902 for building and US$9,683 for contents). Hurricane Ike accounted for 43% of all claims and more than half the total insured damages. The average claim associated with this storm was more than US$43,441.
- The average distance of all claims from the floodplain boundary was 420 meters (1,378 feet). As expected, the average loss outside the floodplain was significantly lower than inside (US$25,180 vs. US$45,180), and there was a clear inverse

relationship between distance from the floodplain boundary and damage intensity across the watershed.

- For Tropical Storm Allison, every meter away from the floodplain boundary translates into, on average, only $18.31 decrease in reported flood damage. In other words, living 0.4 kilometers outside of the floodplain only reduced an average repair bill by $7,365, which still leaves an expected loss of $24, 331. For Hurricane Ike, the distance decay is more severe, indicating that for this storm, inundation better respected floodplain boundaries. In this case, the average per meter damage reduction was $76.12, but households located 0.4 kilometers outside the floodplain still could expect $12,972 in losses because of the destructive nature of tidal surge.
- Distance from the coastline was another important spatial variable when examining flood loss. The average distance for all claims was 9,198 meters (30,177 feet), with claims outside the floodplain being substantially further away from the coast. In contrast, the distance from the coastline for flood losses incurred during Hurricane Ike were significantly closer with a distance of only 4,770 meters (15,650 feet), because this event was surge-based and therefore more directly tied to the coast.
- Spatial interpolation using the kernel density procedure illustrates the spatial gradient of loss across the watershed in relation to the 100-year floodplain. Several prominent hotspots of flood loss are represented on the map, both inland and directly on the coastline. The most severe areas of loss are centered within the 100-year floodplain, but statistically significant clusters extend well beyond these boundaries.
- Overall, the results of this study indicate that the 100-year floodplain may not be a sufficient marker for delineating flood risk and predicting property damage caused by flood events impacting coastal watersheds.
- Statistical results indicate that the local configuration of land use plays an important role in predicting the amount of property damage caused by floods at the parcel level.
    - A surrounding built environment pattern dominated by medium intensity development typical of planned suburban communities appears to have the greatest effect on reducing the amount of insured losses incurred across the watershed. These developments typically have better on-site drainage mechanisms, as well as neighborhood level storm-water infrastructure.
    - In contrast, low intensity, more sprawling development patterns significantly increase flood losses, where a percent increase in surrounding low-intensity development translates into, on average, approximately $1,734 in additional property damage caused by floods. Low-density development patterns can compromise hydrological systems and amplify surface runoff by spreading-out impervious surfaces across a watershed.
    - Palustrine wetlands consisting of freshwater environments significantly reduce observed flood losses over a variety of storm types. In contrast, we did not find any statistical evidence that estuarine wetlands provide flood damage reduction functions, even for surge-based events.
- The statistical results of this study indicate that multiple flood mitigation activities adopted by Community Rating System (CRS) communities in the Clear Creek watershed translate into significant reductions in insured loss at the parcel level.

- After controlling for environmental, proximity, and structural characteristics, structures located within CRS-participating communities experience nearly a 88 percent reduction in mean damage than those not under the program.
- Multiple public information activities (series 300) appear to save property owners significant amounts of flood damage. Critical information about flood hazards, educational projects, and technical assistance provided through these activities influences behavioral changes among homeowners, resulting in significant decreases in the amount of flood loss experienced by residents in the watershed.
- Higher regulatory standards (activity 430) generate the highest mean savings of all analyzed activities. Specific elements that gain credit under activity 430 include development restrictions in the floodplain, implementation of freeboard requirements, and increased requirements for V-zone properties. The total average flood damage reduction from exceeding the minimum criteria of the NFIP to protect existing and future development and natural floodplain functions through series 430 activities in 2009 was approximately $21,023 per parcel.
- Floodplain planning (activity 510) has the largest per-point savings in flood loss among all of the series 500 activities. While this activity may seem less connected to specific properties, in fact, credit points are adjusted according to the number of buildings affected. Maintenance of local drainage systems (activity 540) also has a profound effect on decreasing flood losses.

Key References

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9) AN INTEGRATED ASSESSMENT OF FLOOD RISK REDUCTION THE WEST END OF GALVESTON ISLAND (TAMUG, Brody and colleagues)

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Keywords: Flood losses; Flood reduction; Mitigation; Insurance

Background

The West End of Galveston (figure 1) is extremely vulnerable to damaging floods and hurricane surge. During Hurricane Ike Galveston Island experienced approximately **XXX** in insured flood loss with the West End experiencing considerably more damage per household. A major driver of this damage relative to the Eastern portion of the island is that it is not protected by the existing Sea Wall. As a result, current homeowners have to implement costly household mitigation techniques and pay relatively high premiums for federal flood insurance. To compound matters, changes in the National Flood Insurance Program (NFIP) as a result of the Biggert-Waters Flood Insurance Reform Act will likely increase premium amounts for local residents. These issues, coupled with rapidly eroding beaches and sea level rise, have triggered discussion regarding many structural and non-structural techniques to reduce flood risk and potentially lower insurance premiums.

Figure 1. Study area.

Objectives

This project will involve an integrated economic, engineering, and aesthetic analysis of flood risk reduction to storm surge on the west end of Galveston Island. Researchers at Texas A&M Galveston will examine the implications of constructing a levee in dune (LID) surge barrier along the beachfront and on Route 3005. This interdisciplinary assessment will be the first of its kind and include the following research objectives:

1. Changes in insurance premiums and expected flood losses.
2. Cost-benefit assessment of specific engineering and design alternatives.

3. Aesthetic and functionality considerations of LID barriers.
4. Economic implications of complementary mitigation techniques.

Approach

This assessment is currently in its preliminary stage and so far has leveraged existing data streams, knowledge of flood insurance policies and mitigation techniques, and the expertise from Texas A&M University Landscape Architects to answer the following questions:

- How much have the West End residents paid in damages and premiums?
- What is the difference in premiums and damage amounts by flood zone?
- By how much would the premiums decrease for each of the two proposed barriers?

Results

The 5,838 residential parcels on the West End have suffered approximately $91.2 million in damage in flood loss from 1999-2009 with the vast majority occurring during Hurricane Ike. The A-zone policies experienced approximately the same amount in damage as the V-zone policies, but paid only a fifth of the premium amount (table 1 & 2).

Table 1 & 2. Damage and premium calculation by flood zone.

Damage by Flood Zone (1999-2009)

Flood Zones	Count	Avg Damage	Total Damage
A	2,882	$18,315	$52,785,088
V	1,931	$19,742	$38,122,253
Out	12	$28,210	$338,522
Grand Total	4,825	$18,911	$91,245,864

Average Premium by Flood Zone (2009)

Flood Zones	Count	Avg Premium	Total Premium
A	3,536	$694	$2,452,265
V	2,130	$3,503	$7,460,485
Out	20	$862	$17,233
Grand Total	5,686	$1,746	$9,929,983

Next, approximate adjustments in premium amounts were calculated given the construction of two different barriers: (1) an elevated thoroughfare (San Luis Pass Road), and (2) a fortified dune along the beachfront. The elevation of the San Luis Pass road is likely a poor alternative because nearly a third of the policies (1,613) are in front leaving them exposed to future surge events and only reduces annual savings by half as much ($3.6 million annually) as compared to the fortified dune which protects all of the parcels. These calculations assume that the protected residential property premium amounts would be equivalent to those at 3 feet above base flood elevation under the Flood Insurance Reform Act of 2012.

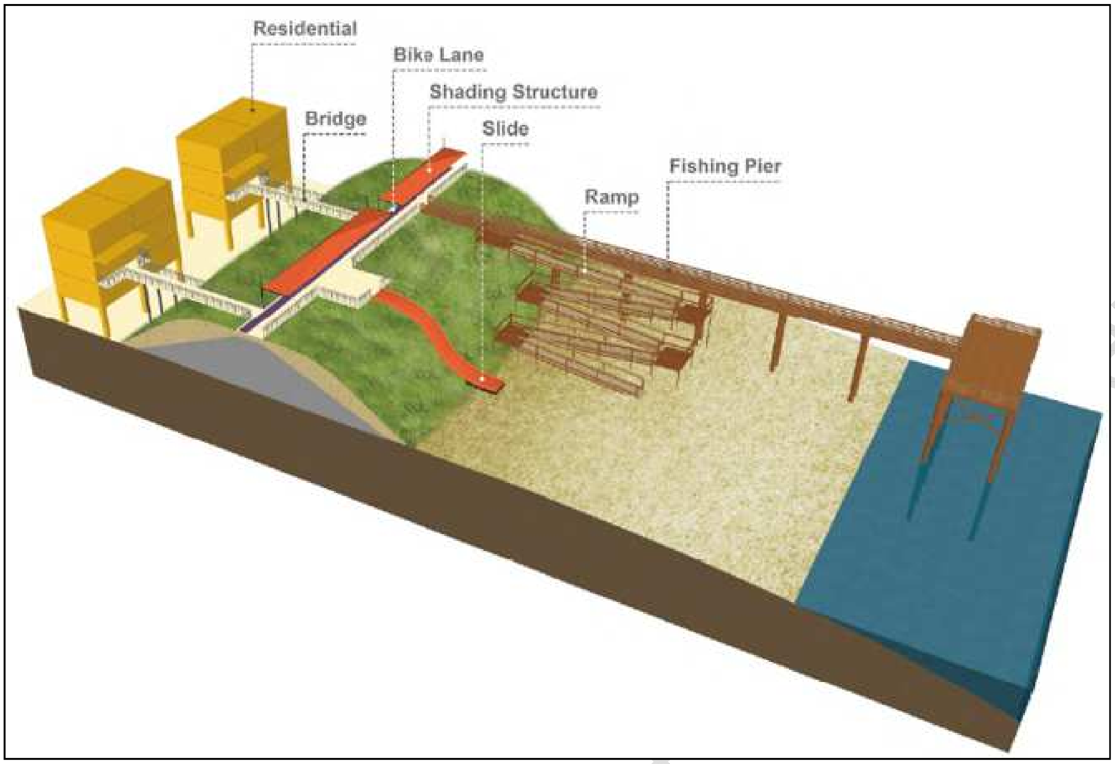

Figure 2. Rendering of a fortified dune. *Source:* Zhang and Guo, 2014

Future Work

Future work will consist of refining the cost-benefit calculations by conducting a thorough assessment of: (1) changes in premium adjustment equations given recently updated NFIP policies; (2) existing residential structural characteristics; and (3) costs of construction and maintenance of barrier types along with other alternatives (e.g. groins, beach nourishment, ecological restoration, etc.). Scenarios can then be generated by calculating the costs associated with another Hurricane Ike if one or a combination of strategies were implemented. Accurate cost and benefit calculations will need to consider the influence of erosion, sediment deposition, and sea level rise.

Interactions

Apart from the invaluable barrier design renderings provided by A&M landscape architects, two presentations were given to different parts of the West End community that allowed for public involvement and feedback into the project.

References

Zhang, Yixun & Guo, Ruisi. 2014. *Ike Dike: Integrated Coastal Dune System.* Presentation given on 7/28/2014.

10) ECONOMIC VALUE OF SURGE SUPPRESSION FROM A COASTAL SPLINE (Bauer College of Business, University of Houston, Gilmer and Perdue)

The primary researchers would be Robert W. Gilmer and Adam Perdue of the Institute for Regional Forecasting, Bauer College of Business, in cooperation with Dr. Hanadi Rafai, Director of the Environmental Engineering Graduate Program at the University of Houston, and one of her students, Daniel Burleson.

The Bauer College of Business at the University of Houston supports the research on surge suppression currently being conducted by Dr. William J. Merrell and his colleagues at the Galveston campus of Texas A&M University. Also known as the Ike Dike project, the study will determine how to best design and construct a coastal barrier that when completed will protect the Houston-Galveston region from Hurricane storm surge. The broad study will consider the barrier's design, engineering, coastal architecture, environmental implications, and economic benefits. The economic benefits are primarily associated with the physical and environmental damages prevented by having the barrier in place.

The Bauer College of Business contributes to this study through an economic analysis of the potential storm damage to the Houston-Galveston area industrial base, particularly the natural gas processing, refining and petrochemical complex. These highly inter-related industries are concentrated on the Gulf Coast, and particularly in the Houston area. For example, the 10-county Houston metropolitan area is home to 8 major refineries that daily process about 2 million barrels of oil; four of the eight largest ethylene complexes in the world are located in the metro area; about 90 percent of US natural gas liquids will pass through the Mont Belvieu area for separation or settlement of futures contracts, and about 70 percent will be processed into plastics or synthetic rubber. These plants find strong economic advantages in water-borne transportation by ship or barge, placing many of them at coastal locations that make them highly vulnerable to hurricanes and flood-related damages. A major expansion of this industrial base is underway, particularly in the petrochemical industry, as global chemical companies increasingly seek out the infrastructure and low-cost feedstock available on the Gulf Coast.

This study would propose to identify those petrochemical plants and refineries that are vulnerable to storm surge, identifying individual facility locations that are potentially at risk, and assessing that risk under various storm surge scenarios. The potential losses to storm surge would depend on the value of the physical facilities placed at risk, as well as the lost production time from the outage. Preliminary discussions with plant operators indicate that the lost production is likely to be the far greater cost in the event of catastrophic water damage, with the plant possibly out of production for 10-12 months.

Once vulnerable plant locations are identified, their production processes and product slates will be identified, with a limited number of detailed studies of the potential effect of surge events on specific chemical plants, refineries and storage facilities. Working with the

SSPEED Center at Rice University, these studies will include potential environmental impacts of the flooding.

The concentration of the Gulf Coast facilities in surge-prone areas offers the potential for a regional event to have large spillover into the broader U.S. economy. The study will determine the indirect effects of the potential storms on U.S. industry, as well as lost consumption induced by associated job and wage loss. The IMPLAN model, a standard and widely-used large-scale model of the U.S. economy would be used to determine the indirect and induced economic impacts.