GAME PLAN:

Framework for Flood Risk Reduction in the Galveston Bay Area

VERSION 1 – December 5, 2014

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This report includes a separate Appendix which contains summaries of research done related to the coastal barrier solution for surge suppression in the Galveston Bay.

Figure on front cover: K. Stoeten (2013)
Section 1 Introduction

1.1 Background

The Galveston Bay Area has a large human population, a thriving economy that is vital to Texas and the United States, and contains the most biologically productive ecosystem in the Gulf of Mexico.

The three counties that surround the Bay (Chambers, Galveston, and Harris) have a combined population of over 4.4 million people making Galveston Bay the most heavily populated watershed in the Gulf Region. Major ship channels run through Galveston Bay serving the ports of Galveston, Texas City and, of course, Houston. The Port of Houston is the busiest export port in the nation generating $178 billion of total economic impact annually. Galveston Bay’s industrial complex contains the largest petrochemical complex in the United States and is of national strategic importance. A report by the Perryman Group for the Independent Insurance Agents of Texas found that a Katrina-like storm that hit the Port of Houston area would result in the losses of $73 billion of gross product over 800,000 permanent jobs and about $2.5 billion in state revenue.

Galveston Bay is also home to a large and productive estuary. The waters, flora and fauna of the Bay drive commercial and recreational activity including commercial and recreational fisheries, ecotourism, bird watching, hunting and boating. The Galveston Bay Estuary Program estimates that over 55,847 hectares (138,000 acres) of coastal wetlands exist around the Bay. These coastal wetlands serve as habitat for the many harvestable species found in the Bay and open Gulf waters.

It is in the Federal interest and the State interest to protect both the economic vitality and the valuable ecosystem services provided by the Bay region’s built infrastructure and natural resources. Hurricane Ike showed that both are vulnerable to storm surge. Hurricane Ike caused over $30 billion in damages to the Houston/Galveston region. Ike also devastated the natural environment; for example, killing over half the Bay’s oyster population and salt poisoning fauna as far as twenty miles inland. Many areas have not yet recovered and, although those of us who lived through Ike think of it as a severe storm, it could have been much worse. The storm track forecast on the morning of September 12th would have placed Ike’s landfall to the west of Galveston forcing the maximum winds and surge over the Island. Had Ike stayed on this officially forecast track, the storm damages would have been about $100B and thousands would have died instead of the dozens who lost their lives during Ike.

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1 This section has been written by dr. Bill Merrell.
Figure 1: The Maeslant Barrier at the entrance of the Port of Rotterdam, the Netherlands protecting the Rotterdam area from storm surges at the North Sea.

Large scale flood protection systems and surge barriers such as those long-used in Europe and now newly constructed in New Orleans provide proven defences against storm surge. A properly designed, constructed and maintained flood protection system will provide protection for the Galveston/Houston region and significantly reduce the risk.

1.2 Purpose of the game plan

This document, a working game plan for Ike Dike research, is designed to evolve and serve a number of purposes. In its present early form (Version 1), it consists of brief reports of more or less individual studies which are focused on a specific aspect of the Coastal Barrier (Ike Dike) overall project. As such, it serves as a means of conveying the progress and rough plans of individual researchers to all Ike Dike researchers. A specific use of Version 1 is to provide a starting point for the December 14, 15 and 16 (2014) meeting of all Ike Dike researchers. A secondary mission of this and subsequent versions is to keep stakeholders and funders fully informed about Ike Dike research progress and plans.

After the December researchers meeting, the team will prepare Version 2 of the game Plan. Version 2 will consist of the individual reports as modified by discussions and interactions at the December researchers meeting as well as new multi-investigator sections that integrate pertinent individual studies into a combined approach to achieve specific research goals necessary to produce an initial, credible cost/benefit analysis for the Galveston Bay region. Version 2 will also contain descriptions of Ike Dike-related projects that are not strongly connected to the initial cost benefit analysis but important to eventually produce better cost/benefit analyses, understand the Barriers’ effects on the region’s natural resources,
future growth configurations and communal and social issues. Appendices will be included to provide more detailed descriptions and links to publications, theses, and formal reports produced by Ike Dike research groups. It will also serve as the starting point for subsequent Ike Dike research planning and in particular the next meeting of the research team.

1.3 Status of the Ike Dike concept
The Ike Dike research group at Texas A&M University at Galveston has formed strategic partnerships with the Bay Area Houston Economic Partnership (BAHEP) and the Bay Area Coastal Protection Alliance (BACPA). The role of Texas A&M Galveston is to develop and disseminate information regarding the coastal barrier concept in a manner appropriate for a public university. BAHEP has been active in working with local communities and decision makers on the Ike Dike concept and advocating its further development and eventual construction. BACPA is a 501c3 advocating surge protection for the Galveston Bay region and funds coastal barrier public outreach through BAHEP and research to Texas A&M and its research partners. The three entities have agreed on “The Ike Dike Concept – A Coastal Barrier Protection System” as a name for the surge protection strategy. So far 20 cities and 10 economic development organizations in the Galveston Bay region have endorsed the Ike Dike concept as the preferred strategy for surge suppression.

A recent development in advancing the Ike Dike concept is interest by the State of Texas. Last session the Texas legislature formed a special joint committee co-chaired by Senator Larry Taylor and Representative Joe Deshotel to examine a coastal barrier system. Senator Taylor and Representative Deshotel have been through in studying the importance of the issue to Texas through hearings and have made trips to the Netherlands and New Orleans to examine the feasibility and appearance of existing barriers. Because the businesses around Galveston Bay are Texas’s biggest economic driver and Galveston Bay is its most productive estuary, it is clearly in the State’s interest to see them protected. The joint committee will produce its first report soon.

Game plan - SSPEED Center statement
Another recent development in Galveston Bay surge suppression research is an agreement between the SSPEED Center at Rice University and Texas A&M University at Galveston to work more closely together. So far, the two research groups have agreed to the following statement.

"The SSPEED Center at Rice University and Texas A&M University at Galveston have been studying strategies for surge suppression for the Galveston Bay Region. SSPEED had been concentrating its efforts on suppressing surge using barriers internal to the Bay system and non-structural alternatives, while Texas A&M Galveston has concentrated on methods to stop the surge at the coast using a continuous coastal barrier – the “Ike Dike” concept.

Both Texas A&M Galveston and the SSPEED Center will continue their research efforts, while collaborating with each other, with an eye towards ultimately combining their various strategies to achieve the best overall solution for the region from an economic, environmental and social perspective."
The SSPEED Center and Texas A&M University at Galveston will coordinate their modelling work and analyses so that the knowledge gained by all efforts can be shared and utilized to more efficiently and effectively reach the development of a regional surge defence strategy for the entire Houston-Galveston area. Each institution is committed to finding the best overall solution for the entirety of Galveston Bay and will work together to achieve that result."

As the two groups work together, more synergies and common interests will appear. It is in everyone’s interest to see that the very best academic research and thinking is fully included in the actionable plans developed for suppressing surge in the Galveston Bay region. As one step in this process, SSPEED researchers have been invited to participate in the December 14-17, 2014 meeting of Ike dike researchers.
Section 2 Framework for risk reduction for the Galveston Bay area

2.1 General
This section provides an outline of a general framework for an integrated feasibility study of risk reduction in the Houston Galveston bay. The framework shows the most relevant aspects and interactions which need to be addressed for considering such large-scale strategic interventions. It is used in Section 3 to address current knowledge and studies to date / identify gaps in our current knowledge and present a roadmap for further work in Section 4.

In Section 2, we first highlight lessons from earlier and comparable large-scale coastal interventions in the Netherlands (e.g. the Eastern Scheldt and Maeslant barriers). Next, we develop a framework for considering risk reduction of large-scale coastal protection systems.

2.2 Lessons from earlier large-scale coastal interventions
Various large scale integrated coastal interventions from the Netherlands (Zuiderzee werken, Deltawerken, Room for Rivers) have been briefly reviewed to determine lessons learned in terms of vision, flood risk concepts and design approach. Some main conclusions are summarized below including some reflections with regards to the Ike Dike/Coastal Barrier:

2.2.1 Vision/purpose
The large-scale Dutch interventions for flood management in 20th century (Zuiderzeewerken, Deltawerken, Ruimte voor de Rivier) are characterized by a multi-purpose vision for the area of interest. Flood risk reduction was (and still is) the most important objective, but improving fresh water supply, creating better road connections, nature restoration and economic development of reclaimed land have been purposes of these plans as well. So far, the Coastal Barrier/Ike Dike solution has been mainly focused on flood risk reduction thus far. It might be considered to widen this viewpoint and include other interests more prominently in the overarching vision/purpose of the Ike Dike. Examples are the improvement of the ecosystem in the bay and the significant reduction of flood insurance premiums due to improved protection of homes in the region.

2.2.2 Flood Risk Reduction
A cornerstone of the various Dutch interventions has been the use of a risk-based decision framework. This framework was developed after the 1953 flood disaster and has been applied to define flood safety standards for the Netherlands. In this framework, the costs or investments of upgrading the protection level (through prevention measures) are compared to the benefits, consisting of the reduction in risk (= probability x consequences). An optimal safety level can be found at which the total costs of the systems are minimal (i.e. economic optimum). It is noted that these safety levels are different for different sub-systems in the Netherlands. A similar approach may be considered for the Galveston Bay area to determine an adequate level of protection for the proposed intervention, and to justify benefits and costs.
Textbox: Risk, CBA and economic optimization

Several definitions of risk exist, but in this document risk is considered as the product of flood frequency (per year) and flooding impacts. Several types of flood impacts should be considered in planning and risk analysis, such as life loss and economic, environmental and societal impacts.

The focus in current studies is on economic risk, meaning that risk can be expressed in $/year or as a net present value in dollars. This also implies that the costs of a certain risk reduction scheme can be compared with the benefits of risk reduction. All these items can thus be expressed in monetary terms. In addition to economic risk (reduction), risk to life can be considered as a separate perspective. For example, one of the leading criteria for deriving the new flood defence standard in the Netherlands (introduced in 2014) has been a threshold for individual fatality risk of 1/100,000 per year. In addition, criteria have been derived by USACE and USBR for dams based on societal risk, the probability of exceedance of multi-fatality events.

A key question in designing and planning flood management systems is the level of protection (or safety standard) that a system should provide. Upgrading the safety level (or flood protection level) will require increasing investments. These investments will contribute to a reduction of the risk (probability x consequences). Since both items are expressed in monetary terms, the risk reduction benefits can be compared with the costs of the risk reduction measures. It is noted that in some countries with limited budgets for flood management, e.g. in the UK, Benefit – Cost (B/C) ratios of more than 3 to 5 are required to invest in projects.

In addition, an optimal level of protection can be found (see figure below) in which the total costs of both investments and risks are minimal. This analysis was made in the 1960’s to derive the safety standards for the flood defences in the Netherlands, which has resulted in the 1/10,000 per year protection level for the most valuable areas along the coast. Results of cost benefit analysis and optimization will also be dependent on the discounting rate and the optimization period that are chosen for determining the net present value of risk reduction benefits.

![Figure 2: Approach for economic optimization](image-url)
The Dutch interventions along the coast are based on the concept of shortening the coastline by closing off large estuaries/tidal basins permanently (for example the Zuiderzee (sea) became lake IJssel) or during a storm only (Eastern Scheldt, Haringvliet, Rotterdam area). A similar strategy was followed in New Orleans after Hurricane Katrina by closing off the 17th Street and London Avenue drainage canals and building a storm surge barrier in the Inner Harbour Navigation Canal (IHNC).

The major barrier plans in the Netherlands have been motivated based on comparisons of closing or shortening the coastline with other flood risk reduction alternatives at strategic level. For example, the Eastern Scheldt storm surge barrier alternative (“semi-closed system”) was compared with raising the levees along the Eastern Scheldt (“open system”) and building a dam in the opening of the Eastern Scheldt (“fully closed system”). A similar study has been carried out in the past for the Rotterdam area in the decision-making process of the Maeslant Barrier (see textbox below).

**Textbox: Protection of the greater Rotterdam area: barrier vs. dike reinforcement**

After the disastrous flood of 1953 in the South-Western part of the Netherlands, the Delta plan was made. This textbox will explain why a barrier is chosen to protect the greater Rotterdam area. More information on other barriers is included in the appendix.

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. To avoid this costly way of protecting against floods, the Dutch government studied the possibility of a storm surge barrier in the New Waterway. 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.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Storm surge barrier</th>
<th>Dike reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total costs</td>
<td>1.45 billion</td>
<td>1.8 billion</td>
</tr>
<tr>
<td>Accuracy costs</td>
<td>+/- 10%</td>
<td>+/- 20%</td>
</tr>
<tr>
<td>Delta safety</td>
<td>1996</td>
<td>2020</td>
</tr>
<tr>
<td>Accuracy construction time</td>
<td>2 years</td>
<td>10 years</td>
</tr>
<tr>
<td>Length coastal defence</td>
<td>35 km</td>
<td>360 km</td>
</tr>
<tr>
<td>Environmental and cultural damage</td>
<td>Limited</td>
<td>Massive</td>
</tr>
</tbody>
</table>

Table 1: Results EIA (see appendix)

Based on the EIA, the Dutch Government chose to construct a storm surge barrier. As technical feasibility of a storm surge barrier was doubted, a contest between contractors was held. Five contractors 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 3) 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 design with two floating sector doors prevailed, as maintenance of this option is relatively easy. The barrier was constructed between 1989 and 1997. Although it is closed yearly for testing, there has been only one closure required to prevent flooding during its operation.
2.2.3 Design approach
The planning and design of large flood protection structures includes the traditional steps, viz. setting design objectives, requirements and boundary conditions, defining alternatives, investigating impacts and costs and selecting a preferred alternative. This process has an iterative character: it converges towards an optimal solution. The impacts on the ecosystem of (partly) closing off tidal basins in the Netherlands have been (and are still) a major concern. Since the Coastal Barrier concept also includes a partial closure of Galveston Bay, potential negative impacts on the ecosystem and associated functions of this system need to be studied in detail to minimize negative impact and/or find proper mitigation or even improving strategies.

Another important lesson from the planning Netherlands is that public perception and support are extremely important to successfully realize these plans. For example, the design of the Eastern Scheldt barrier (initially proposed as a closed dam) was totally changed during the construction phase after environmental concerns were raised against this option, causing years of delay.

2.2.4 Integrated assessment tools
Detailed modelling of alternatives with state-of-the-art modelling tools is generally an important component of planning and design studies. Numerical modelling is often applied to investigate the impacts of interventions on the natural processes such as hydrodynamics, morphology, ecology, etc. Also, modelling is applied to estimate the benefits of coastal interventions through analysis of the (prevented) economic damage and also – more recently – estimating the reduction in loss of life.

A lesson learned from the Room for Rivers and Delta programs in the Netherlands is the benefit of an integrated assessment tool in which all modelling efforts are combined and visualized by a “dashboard”. Such an integrated tool is a very powerful way of showing the impacts of multiple interventions on the overarching objective(s). It appears to be a very effective way for communication with a wider public including communities and decision makers. A good example of an integrated assessment tool is the planning kit (“in Dutch: blokkendoos”) developed for the Room for Rivers program. It contains a database with the results of time-consuming detailed hydraulic models, together with situation sketches, aerial photographs, cost estimates, ecological effects, etc. This tool allows the user to make a
selection among all the available measures and immediately visualize the result of implementing these measures. The Planning Kit has proven to be very effective in facilitating discussion in the planning, design and decision making phases for the Rhine River. Another example of an integrated assessment tool that is more focused on risk reduction is the Simdelta dashboard visualized in figure 4. For the Rotterdam area it shows which levee sections are safe and not safe for a given intervention and future scenario.

![Simdelta screenshot](image)

**Figure 4: Screenshot of Simdelta (developed by T. Rijcken).**

### 2.3 National Research Council Report

In the last decade, the United States have faced severe hurricanes (Katrina in New Orleans, Ike in Houston, Sandy in New York/New Jersey) with very significant damage and loss of life. The United States National Research Council released a report recently, “Reducing Coastal Risks on the East and Gulf Coasts”, which contains a number of conclusions directly pertinent to surge suppression strategies in the Houston- Galveston region. The study was funded by the USACE. In particular the following three conclusions are important and fully supportive of our larger strategy of flood risk reduction as well as Coastal/Barrier Ike Dike research.

**Hard structures are likely to become increasingly important to reduce coastal risk in densely populated urban areas.** Many large coastal cities lack the space necessary to take advantage of nature-based risk reduction approaches alone and will instead need additional hard structures to substantially reduce coastal hazards. Adverse environmental impacts commonly accompany the construction of hard structures, although modified designs are possible to reduce these effects. Coupling nature-based approaches with hard structures to buffer the structures against wave attack provides an effective coastal risk reduction strategy if space allows.

**There is no solid basis of evidence to justify a default 1-percent annual chance (100-year) design level of coastal risk reduction.** The 100-year flood criterion used in the National Flood Insurance Program was established for management purposes, not to
achieve an optimal balance between risk and benefits. There is also no evidence that reducing risk to a 1-percent-annual-chance event is in the best interests of society or that this level is necessarily acceptable to the general public. This level of risk reduction may be appropriate in some settings, unwarranted or excessive in others, and inadequate in highly developed urban areas. Such decisions should, instead, be informed by risk-constrained benefit-cost analyses reflecting site-specific conditions.

**Benefit-cost analysis constrained by acceptable risk and social and environmental dimensions provides a reasonable framework for evaluating coastal risk management investments.** Investments in coastal risk reduction should be informed by net benefits, which include traditional risk reduction benefits (e.g., reduced structural damages, reduced economic disruption) and other benefits (e.g., life-safety, social, and environmental benefits), minus the costs of investment in risk reduction and environmental costs. However, because it is difficult to quantify and monetize some benefits and costs, it is important to expand the analysis to include considerations of difficult-to-measure benefits or costs through constraints on what is considered acceptable in social, environmental, and risk reduction dimensions. Such unacceptable levels of risk may include a level of individual risk of fatality, the risk of a large number of deaths from a single event (societal risk), or adverse impacts on social and environmental conditions that may be difficult to quantify in monetary terms. It is difficult, however, to establish societally acceptable risk standards and requires extensive stakeholder engagement. Setting such a standard requires value judgments, on which not all individuals or groups will necessarily agree.

Comparing the aforementioned conclusions by the NRC with the lessons learnt from earlier large-scale coastal interventions in the Netherlands (see section 2.2), one can find several similarities. The necessity of hard structures to reduce risks is recommended in both cases, as well as the need for a risk based approach to determine the optimal balance between risk and benefits (which is not by default a 1/100yr design level). Furthermore, the life-loss aspect needs to be addressed in terms of individual risk and societal risk. In conclusion, these aspects will be taken into account in developing an integrated risk reduction framework.
2.4 Integrated Risk Reduction framework

Our starting point for the integrated framework to reduce flood risk in the Galveston Bay area is to make a distinction between three sub-systems: the natural system, the flood risk reduction infrastructural system and the societal system (Figure 5). The natural system includes the abiotic and biotic processes in the Houston-Galveston area. Flood risk reduction infrastructural systems (e.g. sea wall and barriers) are human interventions in this area to protect the area of interest. The societal system includes the various ways how society uses the environment (navigation, industry, housing, etc.) together with the institutional side of society (e.g. laws, regulations, governance, etc.).

![Diagram of Integrated Risk Reduction Framework](image_url)

**Figure 5: Generic framework for flood risk reduction infrastructure**

The various sub-systems interact with each other through various mechanisms. For example, the natural system poses boundary conditions to the engineering and societal system. Hurricane winds and surge are examples of this. Reversely, engineering systems can have a significant impact on the natural processes. A coastal barrier system will impact the surge levels in the Galveston Bay, but may also alter the tidal behaviour in the bay during normal conditions. From the societal system, requirements are put forward for engineering systems. An example of such a requirement is the level of protection that the engineering system should provide.

Decision-making about risk reduction measures in the various sub-systems is positioned in the centre of the framework. Flood risk reduction infrastructure in the system have impacts (both positive and sometimes negative) and the trade-offs of these impacts are weighted in a decision-making process. Ax explained, a common tool in the decision-making process is a
cost-benefit analysis in which the costs of certain risk reduction measures are weighed against the benefits of these measures. Because of the complexity due to interactions between subsystems, the design process of flood risk reduction infrastructure has an interactive and iterative character. A certain solution is first designed at a conceptual or sketch level, and will normally be adapted at a later stage to maximize risk reduction, minimize costs and negative effects on other functions (e.g. environment). For example, the opening (or gated area) of a storm surge barrier might need to be increased after more detailed study shows that the initial design will reduce flows into the bay leading to negative environmental effects. The location of storm surge might have to be changed to optimize navigation.

2.5 Application to Galveston Bay area
In this section the framework is applied to the Galveston Bay area.

![Diagram of Generic framework applied to the Coastal Barrier Plan.](image)

**Figure 6:** Generic framework applied to the Coastal Barrier Plan.

In this diagram, the various sub-systems have been detailed with relevant components for the Galveston Bay area. Each part is discussed in detail below. Section 3 elaborates on the studies which have been carried out to address part of these components and identifies gaps in our current knowledge.

**Strategic alternatives and the Coastal Barrier plan:** The left hand corner of this diagram identifies a set of alternatives at a strategic and conceptual level. For example, for the Galveston Bay area such alternatives would include “Do nothing”, the Ike Dike / Coastal Barrier Plan (i.e. shorten the coastline) and one (or more) alternative(s) that focus on...
perimeter protection within the bay ("Open Coast Plan"). In addition, combinations of coastal protection and additional risk reduction measures within the bay could be required to form a multiple layers of defence strategy for protection against outer surge and wind-set up in the bay. Recently Texas A&M at Galveston and SSPEED have agreed to work together to study various (combined) strategies for the region. Eventually, it is desirable to compare these alternatives for the decision-making process (cf. Eastern Scheldt, Maeslant Barrier) on aspects such as costs, risk reduction, environmental, economic and social effects.

Figure 7: Sketch of strategic alternatives and interventions for flood risk reduction in the Galveston Bay area: coastal protection (1) and protection measures along and in the Bay (2). Combinations will also be investigated.

Once a preferred strategy has been identified at strategic level, it needs to be elaborated to a subsystem and component level. Further analysis below focuses on the coastal barrier concept, since this has been the main focus of the Ike Dike research team. Different subsystems can be identified within the Coastal Barrier plan such as the storm surge barrier and the land barrier. Sketch or conceptual designs of these components are necessary to determine investment and operation & maintenance costs. Also a "design" of the management and organizations of these infrastructural components has to be made, including funding mechanisms, roles and responsibilities (see textbox). In the Netherlands so-called water boards are responsible for management and maintenance of coastal and river levees, and Rijkswaterstaat (Dutch USACE) for most of the barriers and dams.
**Textbox: Operations & Maintenance of storm surge barriers**

The design life of a movable barrier is generally 100 to 200 years. During this long period of time, it is important to keep the barrier in good condition to meet the requirements in terms of safety and the environment at an acceptable cost. Experience shows that the average annual cost for maintenance are between a few tenths of a percent and a few percent of the initial construction costs, which over the entire life (even as net present value) adds up to a considerable expense.

![Image of storm surge barriers](image)

**Figure 8: Examples of storm surge barriers in the Netherlands with the Ramspol Barrier in The Netherlands (left) and Ems Sperrwerk in Germany (right).**

Aspects like aging components, climate change and socio-economic developments make the O&M of a movable storm surge barrier a complex task, which requires a sophisticated and object-specific approach. We need to know what mechanisms and/or events could threaten the required functions of the barrier, such as rust, salt intrusion, (hairline) cracks, lightning, ship collision, human errors, software failure, etc. Obviously, not all mechanisms and events occur with certainty and they will not have the same impact. In order to optimize efficiency it is therefore highly recommended to choose a risk-based approach, in which we tune the O&M to the probabilities and consequences of the potential mechanisms and events. In the Netherlands, all large movable storm surge barriers are risk-based operated and maintained.

Starting point for this risk-based O&M approach is a (Quantitative) Risk & Reliability Analysis. Then it is important to choose the optimal maintenance strategy for each of the systems and/or components, i.e. failure-based, time-based or condition-based maintenance, resulting in an optimal set of O&M measures in order to (continuously) satisfy the requirements at minimum cost. Finally we need to monitor the barrier’s performance. Observed failures, and even the fact that no failures occurred, will be used to update the initial Risk & Reliability Analysis and derive an updated O&M strategy for the next period.

A crucial condition is a well-equipped O&M organization. The characteristic of a movable barrier is that it is normally used with a relatively low frequency, varying from a few times a year to only once per 10 or more years. To illustrate: the Maeslant barrier in Rotterdam since its completion in 1997 has never performed a 'real' storm closure. The biggest risk for the O&M organization is that not only little knowledge and experience is gained, but eventually also the sense of urgency disappears, resulting in an increasing contribution of human errors to the probability of failure of the barrier. Again, as an example the Maeslantkering, where human error as much as 30% contributes to the (calculated) probability of failure of the barrier. It is therefore of utmost importance to train the O&M staff, whether through simulations, on a regular basis on the closure procedure and repair of potential failures.
In Asset Management theory, one distinguishes the roles of asset owner, asset manager and service provider. In many cases, the federal government or the state owns the flood protection assets; whereas the local water board or flood protection authority (FPA) serves as asset manager. This means that the FPA is responsible for the barrier’s performance in terms of providing the required safety level and preserving the environment. Agreements on the required performance level and necessary budgets between the asset owner and the FPA should be governed by a service level agreement (SLA). In most cases the FPA will hire private parties as service providers to do the necessary maintenance of the barrier.

Natural processes: The upper part of Figure 5 shows the natural (abiotic and biotic) processes. These processes are relevant since they are both boundary conditions for design (e.g. hurricane surge) and they are affected by the interventions (e.g. tidal flow into Galveston Bay). Since the hydrodynamics are affected by the storm surge barrier during extreme and normal conditions, there might also be impacts on other related aspects such as sediment transport and water quality aspects. On the other hand, “green infrastructure (or Building with Nature)” interventions in the Galveston Bay area may even have a positive impact on the ecological processes. Furthermore, a coastal barrier can serve as a connector of vulnerable natural areas.

Houston-Galveston society: The right hand corner in Figure 5 visualizes the Houston-Galveston society with its activities and governance structure. The area is densely populated and has a dense infrastructure network. A key economic activity is the petrochemical industry with shipping to and from the ports in the region. These activities are linked with the Coastal Barrier intervention because it provides a certain protection against flooding of industrial facilities (e.g. petrochemical sector) and communities along the Bay. The Coastal Barrier intervention may also have other benefits. For example, an indirect benefit of a better coastal protection may be that this area becomes (even) more attractive for private industry. Also, green infrastructure interventions within the Galveston bay could have a positive impact on recreation and fisheries in this area.

Risk Reduction: The central part in Figure 5 defines the objective(s) of the Coastal Barrier Plan. Flood risk reduction is obviously one of the key purposes of this plan. To quantify flood risk reduction, the various corners of this diagram provide different inputs. The total costs of the Coastal Barrier Plan can be estimated once designs of all relevant features are available. Usually a design at a conceptual level (quantities, dimensions, types of interventions) will allow estimation of investment costs at a reasonable accuracy. Also, operations and maintenance (O&M) costs have to be included. The probability of flooding and the associated inundation characteristics follow from a detailed regional analysis of hurricanes, flooding and the return periods. These characteristics are combined with the societal system to estimate economic damage and loss of life. By doing this analysis with and without a coastal barrier plan, the risk reduction benefits can be identified. Note that some barrier systems will also involve benefits, e.g. improved transportation routes and positive spin off for the regional economy.
Section 3. Ike Dike Research program

As part of the Ike Dike research program, various studies have been carried out in the past years to investigate certain aspects or components of the Coastal Barrier solution. This section provides an overview and discussion of the work using the framework of the previous section. Summaries of the extensive multi-disciplinary research work on the Coastal barrier are included in the appendix.

The figure below shows the various studies in the framework as proposed in Section 2. This figure also highlights which aspects have been studied (dark colour) and have not been addressed yet (light colour) to our current knowledge. This is further elaborated in the next sections.

![Figure 9: Generic framework applied to the Coastal Barrier Plan, with indications of focus of current research efforts.](image)

### 3.1 Coastal Barrier Solution

Various components of the Coastal Barrier solution have been studied in the past years. Most of this work has been carried out by MSc students at Delft University. The work is summarized in Appendix 1. The main findings are presented in this section. The Coastal Barrier consists of land barriers on the Galveston Island and Bolivar peninsula and a storm surge barrier in the Bolivar Roads.
### 3.1.1 Storm surge barrier

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. A minimal opening of about 70% of the original opening is aimed for. Due to the large size of the Galveston Bay, there is an opportunity to construct a barrier that only partly blocks the surge, leading to cost savings. The key hydraulic parameter for this design is the maximum head difference between the bay and the open coast (both positive and negative). Another important aspect for the design of the barrier is the subsoil, upon which the barrier will be built. The subsoil in Bolivar Roads consists mainly of soft and firm clay layers, before reaching a strong bearing sand layer at MSL-40m.

The most suitable gate types for the navigational section of the storm surge barrier are a barge gate and a sector gate, which was applied for the Maaslant barrier). A major disadvantage of applying sector gates to this case is that they cannot easily deal with negative hydraulic heads. TU Delft, RHDHV and IV Infra made a sketch design of a steel barge gate for the navigational section. Karimi investigated options for a barge gate consisting of concrete. An alternative was investigated by M. van Breukelen, who looked at inflatables as storm surge barriers.

![Impression of the barge gate and proposed gate in the next phase of the study](image)

**Figure 10: Impression of the barge gate (left) and proposed gate in the next phase of the study (right) (Jonkman et al., 2013).**

In an initial design a shallow-founded caisson barrier with vertical doors appeared to be the most appropriate barrier type for the environmental section in the thesis of de Vries (2014). However, during the design process it was concluded that the clay layers give foundation issues. Given these issues, other alternatives for the environmental barrier should be investigated.

It is noted that the design is made to allow navigation by Post-Panamax vessels, which requires the channel to have sufficient depth and width. This will influence the flow patterns through the Bolivar Roads, which will have to be accounted for in future studies.
3.1.2 Land barrier

Studies have been performed on various aspects of the land barrier(s). These include a design for the Bolivar peninsula. The thesis from Nick West has investigated various concepts for a coastal levee by means of prototype experiments. It showed that a fortified dune or levee in dune would be a promising option. The architectural integration has been addressed by Texas A&M (Bardenhagen and Newman). Furthermore, sketch designs of the land barrier on Galveston Island have been made by a MSc project group of the Delft University of Technology. The (civil) engineering and landscape design need to be combined to come to an integrated design, and a design analysis at the system level (both for Galveston and Bolivar islands) is recommended.

Figure 11: Birds eye sectional view of caisson barrier with vertical drain soil improvement (de Vries, 2014).

Figure 12: Engineering design of land barrier (Figlus, 2014)

Figure 13: Architectural design of land barrier (Newman, 2014)
At this moment, the scales of the available civil engineering design of the land barrier (sketch / concept level, no system-wide proposal) and the architectural design (very detailed renderings) do not seem to match yet. This requires further design of the land barrier.

3.1.3 Next steps
From this overview, it can be concluded that sketch or conceptual designs of parts of the Coastal barrier system are available (e.g. parts of the storm surge barrier). Also very rough cost calculations have been made of these components. However, no comprehensive system design at a sketch / conceptual level is yet available. This is required for estimating costs, the analysis of effects and communication of the Ike Dike system to a broader public. Elements of the barrier system that require further elaboration to come to a first conceptual design are:

- Sketch designs have been made for the navigational section of the storm surge barrier. Further engineering is required regarding the foundation, scour protection, hinge, wave impacts and dynamic stability.
- The environmental section of the storm surge barrier, for which the existing caisson design (MSc thesis De Vries) gives issues for the foundation due to the presence of weak subsoil in the Bolivar Roads. This aspect needs further attention in the next step.
- The engineering design of the land barrier. Important aspects include the required dimensions, type of coastal levee (fortified dune and other alternatives etc.) and cost estimate depending on type of structure and material availability. This would have to build on existing studies by Texas A&M to come to a system level design.
- The architectural design/landscape integration of the barrier. For the land barrier initial steps have been made, but this aspect is not studied thus far for the navigation/environmental sections of the barrier. This needs attention in the next step.
- Design and costs of small barriers in the passes / inlets, and the need for additional interventions within the bay for protection against the local surge. Possible features include local barriers, e.g. in some of the bayous, protection of Galveston against back-surge.
- In addition to research on protection measures, additional research and design work is required on mitigation measures that are used in the United States. It could be investigated how measures such as land use planning, adapting existing buildings, building codes, insurance and evacuation can be a part of the overall strategy for risk reduction for the region. Also, different ongoing studies on elements of the system use different boundary conditions w.r.t. level of protection and surge. One set of boundary conditions is desirable to come to a consistent design.

It is recommended to elaborate these features at a sketch or conceptual level to come to an overall plan. Based on evaluation with surge and flood risk models, adaptations to the designs will likely have to be made (iterative design process).
3.2 Natural system
Regarding the natural system, the studies by the various members of the Ike Dike team have focused thus far on the hydrodynamic behaviour of the Texas coast and Galveston Bay during extreme conditions.

3.2.1 Normal conditions
Ruijs (2011) studied the effects of the Ike Dike Plan during non-storm conditions. A 2DH numerical model was set up to quantify the hydrodynamic impact of the restricted Bolivar Roads opening due to the presence of the gates. This model has been forced with time-dependent wind (uniform in the area), offshore tidal constituents and fresh water inflow. Based on detailed verification, the model has proven to be reliable for the central part of the Bay. The results from the East Bay and West Bay should be handled with some caution due to some discrepancies between modelling results and measurements.

Using this model, Ruijs (2011) investigated the impact of gates in Bolivar Roads on both the vertical and the horizontal tidal movement in the Bay. The constriction due to the gates was assumed to be 40 – 60% in this work but no design had been made at that time. For this constriction range, the tidal range decreases with 10 – 40% according to the model results, see Figure 9. The maximum current speeds during the tidal cycle in the opening increase up
to 1.3 – 1/6 m/s, whereas the maximum current speeds inside the Bay decrease with 20 – 40%.

Other aspects such as effects on morphology, water quality and ecology were studied with much less depth and in a qualitative way. Hence, these conclusions have a preliminary character. Ruijs (2011) hypothesized that the marsh and coastline erosion within the Bay may be further enhanced due to the blocking of sediments and reduction in current speeds/tidal prism within the Bay. Also, the residence time might go up with a factor 2 – 3 according to Ruijs (2011). Potential mitigation strategies to reduce these impacts are 1) to maximize the opening and/or 2) to study the potential of compartment dams in the Bay (e.g. Eastern Scheldt). Based on the results from Ruijs (2011), the various design efforts (e.g. for the navigation and environmental opening, see section 3.1) have been focusing on maximizing the opening to at least 70% of the original opening (i.e. design criterion). The impact on the tidal amplitudes is less than 10% if this design criterion can be met (see Figure 15).

3.2.2 Hurricane conditions
Stoeten (2013) developed a simplified probabilistic hurricane surge model for Galveston Bay. In this model, the meteorological forcing is coupled with the hydrodynamic response resulting in a first-order estimate of the surge in Galveston Bay. The hydrodynamic behaviour but also the geometry of the Bay (circular Bay with constant depth) was simplified in order to be able to evaluate a large number ($10^5$) of storm scenarios. Hind casts of historical storms show that the model has a typical error of +/- 0.5m for an individual storm at a certain location.

The model simulations show that the surge within the Bay is a combination of local wind setup and inflow. The local wind setup can contribute up to 50% of the total setup in the Bay depending on storm track and intensity. The computational results at the open coast near Galveston show a good match with the numbers based on extrapolated measurements.
For the current situation without Ike Dike, it follows from the probabilistic computations that the extreme surge levels \((10^3 - 10^4 \text{ yrs.})\) at the northern and western part of Galveston Bay are higher than at the open coast and eastside of the Bay. The Coastal barrier reduces the surge levels within the Bay with 2 – 3 meters depending on the return period.

![Extreme surge level statistics with and without Coastal barrier (Stoeten, 2013).](image)

The simplified hurricane surge model of Stoeten (2013) has also been applied to investigate the required crest elevation of the storm surge barrier, and this is also addressed in ongoing work by Rippi at TU Delft. The original elevation of the barrier was set at the same height of the Galveston sea wall (about 5m+MSL). A lower barrier elevation probably reduces the costs, but it results in more inflow into the Bay because the storm surge peak will then overtop the barrier crest. It turns out that a lower barrier with a height of 1 - 2m+MSL still provides the same surge reduction compared to a 5m+MSL barrier elevation. The small extra inflow during the peak of the storm can easily be stored within the Bay without raising the surge levels significantly.

Jackson State & ERDC (2014) have been working since 2013 on detailed hurricane surge and wave modelling for the Texas area. For this purpose, the Coastal Storm (CSTORM) modelling system has been applied for with and without Ike Dike conditions. To date, 26 storms have been evaluated including Hurricane Ike, 21 severe storms with a 900mbar central pressure on various tracks, and 4 storms ranging from 975 - 900 mbar making a direct hit over the City of Galveston. The Ike Dike has been modelled as a monolithic barrier with the same crest height as the Galveston sea wall.

The modelling results provide very detailed insight in the hydrodynamic functioning of the Texas Coast and Galveston Bay during extreme conditions. Similar to Stoeten (2013), the tilting effect due to local wind setup and filling effect due to inflow are recognized as two important processes for understanding the surge in Galveston Bay. Also, the feedback between these processes (i.e. more inflow results in less tilting because of larger water depths) is highlighted. Initial results provide insight in the 100-yr and 500-yr surge levels without Ike Dike. From a limited number of storms (#121, #122, #155), the surge reduction in the Bay is 1 – 3 meter due to the Coastal barrier (see e.g. Figure 17) An assessment of the surge level statistics with and without Coastal barrier is not yet available.
Jackson State & ERDC (2014) also provide guidance on the use of sea level rise scenarios. It is concluded that the low, intermediate and high scenarios of relative sea level rise are +1, +1.5 and +3ft in 2070, respectively. For feasibility purposes, the intermediate scenario is recommended (+1.5ft) for a 50-year time span.

### 3.2.3 Next steps

From the various studies presented above, it can be concluded that the main focus has been on hydrodynamics (both for normal conditions and hurricane conditions). Two different modelling approaches have been followed to define the impact of the Ike Dike on hurricane surge in Galveston Bay thus far: detailed ADCIRC modelling (Jackson State & ERDC) and a simplified hurricane surge model (Stoeten, 2013). Other models are used by other groups, e.g. by the SSPEED center. To compare both approaches, the 100-yr surge levels at similar locations along the Bay have been listed in the table below. It turns out that – except for the bayside of Galveston – the 100yr values of both models are very similar. An initial assessment suggests, however, that the model of Stoeten (2013) predicts lower surge levels for higher return periods than the results from Jackson State & ERDC (2014). It should be noted that Stoeten did not look at the impact on water levels in the Houston Ship Channel.

<table>
<thead>
<tr>
<th>Place</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>100yr (m)</th>
<th>Place</th>
<th>100yr (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Porte</td>
<td>29° 38' 46&quot;</td>
<td>95° 00' 42&quot;</td>
<td>4.3</td>
<td>North</td>
<td>4.2</td>
</tr>
<tr>
<td>Texas City levee</td>
<td>29° 35' 27&quot;</td>
<td>94° 56' 24&quot;</td>
<td>3.8</td>
<td>West</td>
<td>3.6</td>
</tr>
<tr>
<td>Galveston (bayside)</td>
<td>29° 10' 18&quot;</td>
<td>94° 49' 49&quot;</td>
<td>3.6</td>
<td>South</td>
<td>2.9</td>
</tr>
<tr>
<td>Galveston (Oceanside)</td>
<td>29° 07' 17&quot;</td>
<td>94° 16' 47&quot;</td>
<td>4</td>
<td>Open Coast</td>
<td>3.9</td>
</tr>
</tbody>
</table>

*Table 2: Comparison between 100yr surge levels in Galveston Bay area.*
Thus far, solid baseline information about the hurricane surge probabilities for the situation without and with a Coastal Barrier solution for a large range of return intervals is not yet available. Further analysis on the impact of the recurrence intervals and also the impact of different design optimizations (e.g. lowering the barrier) on the surge levels are required. Both hurricane surge modelling approaches presented above have advantages and disadvantages regarding accuracy, computation time, physical insight, etc. It is recommended to develop both modelling tracks further in the next steps of this research.

Other aspects (morphology, ecology) have not been studied in depth thus far. Ruijs (2011) provided some hypotheses how the barrier could impact these aspects. Especially the environmental effects (impact on habitats, organisms) of the Coastal barrier solution (both positive and negative!) are important. This needs to be further studied in detail in the next steps. Also, the short-term and long-term morphological behaviour of the Texas coast - Galveston bay system needs careful attention in the next steps. The storm surge barrier may affect the tidal behaviour/prism which probably results in a morphological response inside but also outside the Galveston Bay. Also, the morphodynamic behaviour of a land barrier during hurricanes and non-hurricane conditions needs to be studied in more detail.

### 3.3 Houston-Galveston Society

So far, the various studies by the Ike Dike team have mainly focused on economic impacts of flooding around the Bay.

The study by Texas A&M (Brody and Atoba) investigates the reduction of direct flood damages to residential and industrial properties due to the Ike Dike. It shows that the building losses due to a coastal barrier could be reduced from $3.7 billion to $1.2 billion (for storm A). More detailed and higher resolution studies are available for specific areas, such as the Clear Creek watershed (Brody et al).

The institute of economic forecasting (Gilmer et al.) are setting up a study to determine the potential storm damage to the Houston-Galveston area industrial base, particularly the natural gas processing, refining and petrochemical complex. The IMPLAN model, a standard and widely-used input – output model of the U.S. economy would be used to determine the indirect and induced economic impacts. The IMPLAN model has also been used in a study by Texas A&M (Men Davlasheridze et al.). Preliminary findings show that indirect and induced economic damages can be substantial (around 30%) when compared to direct losses to buildings and infrastructure. The approaches developed will also give insight in damage reduction in terms of savings on flood insurance and disaster programs.

### 3.3.1 Next steps

In order to come up with a comprehensive analysis for the damage and risk reduction of the Ike Dike one set of damage models and approaches, as well as a standardized data basis for the region has to be developed. Results of the various studies have to integrated and aggregated to come up with total damage and risk reduction of proposed solutions.

The studies (will) provide important insights in the (avoided) economic damages for the region. To do this in terms of risk reduction, return periods of various flood scenarios need to
be identified\(^2\) (see discussion on the risk framework in the next section). In an integrated assessment by Texas A\&M (Brody and Blessing) for Galveston Island, the costs of interventions, economic impacts and functional and aesthetic implications are addressed.

Currently, economic damages of flooding have been considered. It would be highly relevant to assess life loss (reduction) as one of the main aims of the Ike Dike is to protect people. Life loss models have been developed based on hurricane Katrina, but these can be further refined and applied to HG Bay. Also, other functions have not yet been addressed in detail (e.g. recreation, fisheries, etc.) in relation to the Ike Dike and this would be a topic for further work.

3.4 Flood risk

One of the main objectives of the Coastal Barrier Plan is to reduce flood risk in the Galveston Bay area. For this region, Stoeten (2013) has set up a preliminary risk model in his MSc thesis. In a simplified manner, it includes the hurricane surge probabilities and the potential damage, which are coupled to evaluate different risk reduction strategies and an optimal level of protection.

In ongoing Ike Dike studies the underlying building blocks of risk are being investigated (such as hurricane surge, damages and interventions - see previous sections). However, no fully integrated model has been developed yet to integrate these findings in order to quantify the flood risk (reduction) for a given system configuration. This implies that there is no clear insight in the current risk (do-nothing option) and the reduction of risk to an optimal or desired level by certain interventions. In order to quantify benefits of the Ike Dike (or some other) solution, risk reduction would have to be calculated. In such an analysis the risk in the current (do nothing) situation would be compared with residual risk under various system interventions.

3.4.1 Next steps

It is therefore recommended to develop a simplified risk model that could be used to evaluate various interventions and system configurations. It would integrate and couple outcomes of the hurricane, damage and intervention studies\(^3\). This type of model framework has also proven to be very beneficial for New Orleans and other situations (see textbox). The model frameworks of New Orleans and Stoeten could serve as a starting point for setting up an integrated risk model for the Galveston Bay area. Database and GIS components will be a part of this modelling approach and the initial analysis on reduction of economic losses (Texas A\&M) could be extended.

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\(^2\) For example, in the study on economic impacts by Brody and Atoba, one question for future work is which return periods are associated with the storms (A to D) that are investigated.

\(^3\) The alternative is to couple existing sets of (complex) models for surge and economic impact. Since a probabilistic approach is needed with many scenarios, coupling existing complex models would likely result in model framework that is less suitable to evaluate various system configurations relatively quickly.
(Simplified) flood risk models for New Orleans

The advantage of these simplified risk models has been shown for the New Orleans area in the aftermath of Katrina. A risk modeling framework was developed as part of the studies by the Interagency Performance Evaluation Taskforce (IPET). This model integrates the information from underlying modeling studies on hurricane surge, economic impacts etc. Instead of using the underlying models, the risk framework often uses extracted and simplified data such as databases with return periods of surge levels for a given location. This information is based on more complex and rigorous underlying models for hurricane surge, levee safety and flood damage.

Such a risk model can be used to evaluate the risk in a system and the effect of proposed interventions in a relatively quick manner. An example has been the evaluation of the cost effectiveness of building inner levees (compartimentalization) in New Orleans against raising the outer perimeter of the system.

![Risk Modelling Framework](image)

Figure 18: Risk modelling framework used in the IPET study for New Orleans (IPET, 2009).

Also, a simplified risk model was set up of the New Orleans East area to study the investments and the reduced risk in order to find the optimal safety level. In this study, both hurricane and rainfall hazard were included in the analysis.

The national risk study in the Netherlands (VNK) uses a framework similar to that used by IPET to assess local and national flood risk levels for the nation.
Section 4. Outlook and recommendations

This section provides an outlook and recommendations for next steps. A distinction is recommended between three phases:

- Short term (March 2015): Indicative Benefit/Cost ratio Coastal Barrier Plan
- Midterm (July/August 2015): Feasibility Study for a Coastal Barrier Plan
- Long term (July/August 2016): Integrated Risk Reduction study for the Galveston Bay area

These phases are discussed in detail below as a basis for discussion and planning. Exact timing and contents of these phases will eventually depend on various processes and boundary conditions.

4.1 Short-term focus: Indicative Costs and Benefits Coastal Barrier Plan (March 2015)

The main objective on the short term (March 2015) of the research consortium led by Texas A&M Galveston is to give an indication of costs and benefits (+/- 50%) of the proposed Coastal Barrier Strategy (see figure 19). In view of what has been done to date, insight is needed in the following:

- **The costs of the proposed Coastal Barrier Strategy**: This requires a design of the entire system (storm surge barrier, land barrier, interventions within the bay) at a sketch or conceptual level. Main focus to date has been on the storm surge barrier in the Bolivar Roads including a rough cost estimate of this element. However, at this moment not all elements of the barrier system have been designed at a system level. Further research and design of the land barriers is needed, as well as an analysis of the need for interventions in the bay (e.g. protection of the back side of Galveston Island) to provide an indicative cost estimate of the Coastal Barrier strategy.

- **The benefits consist of risk reduction due to the Coastal Barrier Strategy**: It also has to be determined how much the proposed Coastal Barrier Strategy reduces (the probability of) flooding within the bay. By linking this to damage modelling, the risk reduction (in terms of avoided damages) can be estimated, determining the benefits of the proposed solution. It is recommended to assess and quantify the effects of the Ike Dike on the return periods of flooding and damages.

It is expected that this results in a positive benefit/cost ratio of the Coastal Barrier Strategy based on earlier work. This result may feed into the request for additional funding for the mid-term and long-term objectives.
4.2 Mid-term focus: Comprehensive Feasibility Study Coastal Barrier Plan (July/August 2015)

The mid-term objective (July/August 2015) of the research consortium led by Texas A&M Galveston is to provide a comprehensive feasibility study of the proposed Ike Dike / coastal spine strategy. Next to a more detailed analysis of costs and benefits (+/- 30%), also the impacts (negative and positive) of the Coastal Barrier Plan should be well documented. The following items need attention in this phase:

- The design of the Coastal Barrier strategy may be further fine-tuned to a conceptual and detailed level through several optimizations/designs (e.g. crest elevation of the storm surge barrier). Additional geotechnical information is recommended to fine-tune the foundation and thereby narrow down the cost estimate of the surge barrier. Also, it is recommended to put effort into the landscape integration and architectural design of this Coastal Barrier and create an attractive design/architecture of the barrier.
- Risk reduction can be optimized through the Coastal Barrier strategy configuration. For example, tolerable overflow over and leakage through storm surge and land barriers has to be determined, as well as the added value of protection features within the bay. In doing so, a required/optimal level of protection of the system can be chosen, based on the earlier mentioned benefit cost ratio.
- To support planning, optimization and Cost Benefit Analysis of the Ike Dike it is recommended to set up a simplified risk model which couples (reduction of) surge and wave probabilities, damages and effects of interventions.
- Additional surge and wave modeling is recommended for a larger suite of storms. Also, detailed wave and flow modeling around the barrier to define more accurately...
the static and dynamic loadings at the structure (both in closed position but also during opening and closing).

- Environmental changes of proposed Coastal Barrier strategy have to be evaluated using models for water quality and environmental effects. Also options have to be investigated to optimize the system configuration and/or to improve the environment (e.g. Building with Nature interventions in the Bay). Effects on other functions, such as navigation, tourism etc. would have to be investigated too.
- It would be highly relevant to assess life loss (reduction), as one of the main aims of the Ike Dike is to protect people. Life loss models have been developed based on Hurricane Katrina, but these can be further refined and applied to the Galveston Bay area.
- Public perception and support of this strategy needs to be further elaborated. Also, impacts on other functions in the region (fisheries, recreation) must be further assessed.

Figure 20: Midterm focus on Feasibility Coastal Barrier Plan.

4.3 Long-term focus: Integrated Risk Reduction Study for the Houston/Galveston area (July/August 2016)

The long-term objective (July/August 2016) is to provide a comprehensive report of the various strategic alternatives for the Houston-Galveston area including the "Do Nothing" option. The objective of this report is to provide a sound scientific basis for decision-making on the preferred risk reduction strategy in the region. Each strategic alternative needs to have the same level of detail and a relatively accurate estimate is required of costs and benefits to make this decision. The following items may require further study in this phase:

- Detailed surge and wave modelling is required in this phase to make more detailed designs and provide accurate cost estimates. Also, a detailed analysis is
recommended how different climate change scenarios affect the choice of certain strategies.

- The risk reduction of the various strategies (Coastal Barrier, Open Coast, Do nothing, other) must be compared with the same level of detail. It is also recommended to look at other goals next to risk reduction. For example, an ecological improvement of the Bay could be an additional goal of the overall strategy.

- Further fine-tuning of the design elements is required to provide a more accurate cost estimate for both the initial investment costs but also the operation & maintenance costs. This may require more detailed geotechnical (e.g. detailed borings for the foundation of the storm surge and/or land barrier) and hydraulic (e.g. detailed wave modelling near the structure) information.

- In this phase, the simplified risk model can be extended with other strategies (“Do nothing”, “Open Coast Plan”). The results of this simplified risk model for the different strategies can also be visualized in an interactive way to provide a platform for communication with communities/decision-makers.

Figure 21: Long term focus on Integrated Risk Reduction for the Houston-Galveston area.
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