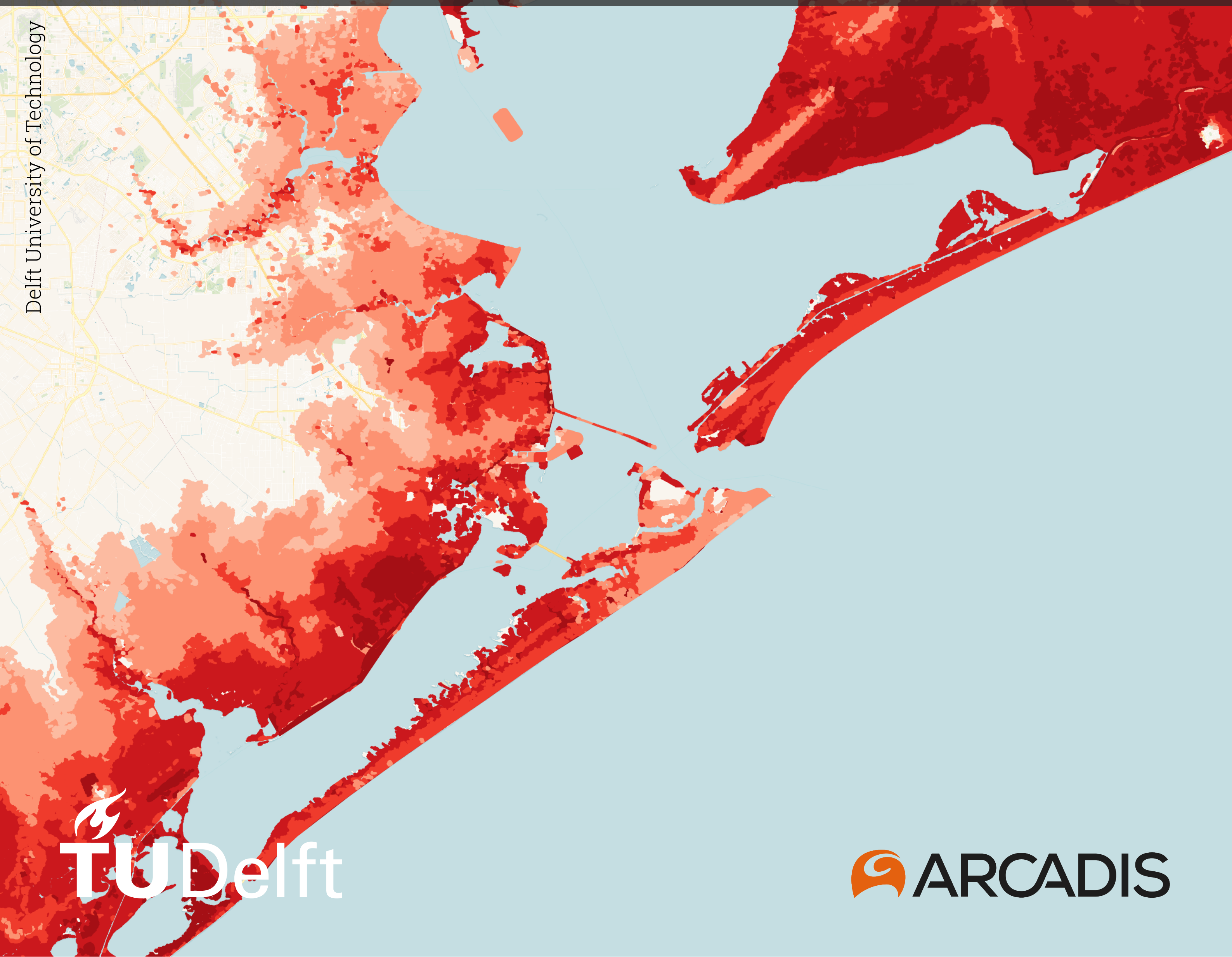
Dynamic Adaptive Policy Pathways for flood risk management in Galveston Bay

Making informed flood defence decisions for an uncertain future

M.W. van Herwijnen



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Dynamic Adaptive Policy Pathways for flood risk management in Galveston Bay

Making informed flood defence decisions for an uncertain future

by

M.W. van Herwijnen

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Cover: Inundation map of the Galveston Bay area for the 100-year storm surge and rainfall event
Style: TU Delft Report Style, with modifications by Daan Zwaneveld

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Preface

This report marks the culmination of my Master's thesis, which is the capstone of years of laborious studies in Civil Engineering at TU Delft. It concludes my academic journey, which has been defined by learning and growth. I am extremely grateful to my family and friends for supporting me through these defining years.

I would like to thank a few people who have enabled me in this research. Foremost, I want to express my sincere appreciation to Erik van Berchum, my company and daily supervisor at Arcadis, for his unwavering assistance and expertise during the entire process. From model issues to reporting advice, you were always a tremendous help, and your insights significantly enriched the quality of this work. I am also grateful to Arcadis for providing me the opportunity to undertake this project at their company. The hydraulic engineering team at the Rotterdam office provided a supportive and enjoyable environment for writing my thesis.

Special acknowledgements are owed to the members of my university graduation committee. Bas Jonkman, thank you for the critical feedback during the progress meetings and for always asking the right questions to make me think more deeply about my choices. Maria Pregnolato, thank you for the extensive feedback on my report and for lifting the reporting style to a higher level, even during a difficult time. Lastly, Jos Timmermans, thank you for your advice on the DAPP approach and robust decision-making, which were completely new topics for me.

While the journey of writing this thesis was solitary at times, a fine group of graduates formed at Arcadis. I want to extend a special thanks to Rushil, Kevin, Dorine, Gerwin and Anne for their companionship and support. The drinks and many afternoon games of table tennis were delightful, and the relationships we forged along the way were invaluable.

M.W. van Herwijnen
Delft, March 2024

Summary

The Galveston Bay area is one of the United States' biggest growth regions. It is home to roughly 5.4 million people and contains 30% of the U.S. crude oil refining capacity. However, the region is under pressure from devastating hurricanes, causing billions of dollars in damages. Hurricane Ike in 2008 and Harvey in 2017 are the most recent examples. Only small and localised flood protection measures are currently in place. Therefore, several parties have performed research and developed flood risk protection and mitigation plans for the Galveston Bay area. However, limited research has been conducted to compare the plans under a wide range of possible futures. Furthermore, the timing of the implementation of the measures has not been studied.

However, the detailed modelling of flood risk management strategies for an uncertain future poses several challenges. Firstly, a fast but accurate flood risk model is required to calculate the effect of many combinations of flood risk reduction measures under a wide range of future conditions. Secondly, the results must be made understandable to a wide audience, not just to hydraulic engineers. Dynamic Adaptive Policy Pathways (DAPP) provide an easy-to-understand overview of the results. This study aims to inform local policymakers of the effects of (combinations of) measures in a wide range of future scenarios and identify robust measures for the Galveston Bay area that are effective in many possible scenarios. Robust solutions are important as they allow for measures to be implemented now, but they also allow for change in the future as conditions might change. The main research question of this thesis is:

How can Dynamic Adaptive Policy Pathways support decision-making in the Galveston Bay area?

To answer this question, a novel framework has been developed to analyse the flood risk for many plausible future scenarios. The framework consists of several steps and can be divided into two parts: the setup phase and the results analysis phase. The first step of the framework is to analyse the study area, collect necessary input data for the FLORES model and perform any required data preprocessing. FLORES requires elevation, storm surge, rainfall, population, development, uncertainty data, and more. The second step is to set up the model for the study area. This step identifies the most risk-prone areas, and flood protection or mitigation measures are defined based on the proposed plans. Next, it validates the results of the hydraulic modelling and implemented measures. The results of the entire flood risk screening are analysed in the second phase of the framework. The screening repeats the flood simulation for each combination of measures, future scenarios and hydraulic boundary conditions. The results of the screening are used in two ways. Firstly, questions from local policymakers are answered based on specific analyses of the results. Secondly, a broad analysis is performed on the entire result set to find interesting system behaviour, identify tipping points and establish effectiveness regions. Lastly, the dynamic adaptive policy pathways are constructed based on the analysis of the screening results. Based on the pathways map, policymakers are informed on robust measures, dead ends, and the effects of uncertainties on the system and are able to compare strategies in different future scenarios.

The framework is applied to a case study of the Galveston Bay area. Analysis of the land value and population data of the area shows a concentration of value and people on the west coast of the bay and in the city of Galveston. The east side of the bay is nearly uninhabited and represents little economic but great environmental value. Six measures have been identified based on the proposed plans, and all combinations of these measures have been evaluated. Figure 1 shows the location of the measures in and around Galveston Bay. The land barrier follows the coastline along Galveston Island and Bolivar Peninsula. The storm surge barrier closes the gap in the coastline at Bolivar Roads and is the connecting element between the two parts of the land barrier. Behind the barrier islands, the Midbay

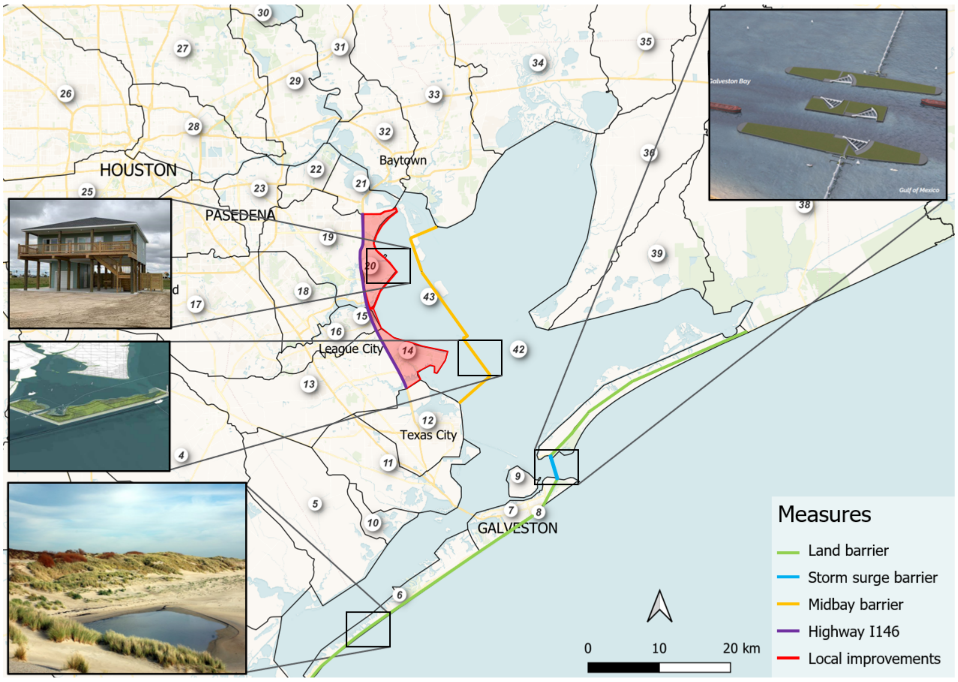
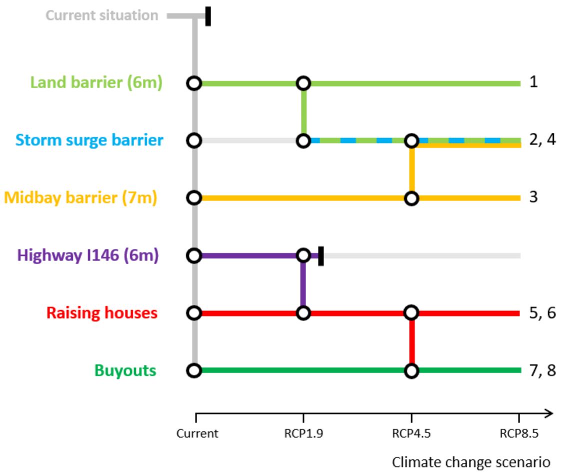


Figure 1: Map of the Galveston Bay area with the locations of the considered measures

Barrier cuts through the Galveston Bay and protects the valuable west coast of the bay. Further inland, the Highway I146 levee consists of raising the highway and adding storm surge gates. Lastly, local improvements can be made along the west coast of the bay by raising houses or buying out properties and returning the area to nature.

The screening has shown that implementation of the land barrier and the storm surge barrier at Bolivar Roads is crucial to achieving the largest flood risk reduction in the Galveston Bay area. This combination alone leads to a risk reduction of $3,501 million per year and protects 72 thousand people from flooding annually in the current scenario. The upfront cost of these measures is $7,699 million. Flood risk of local inhabitants and economic value will benefit most if work on these measures is prioritised. However, if this measure is deemed too costly, the best alternative is to build the Midbay Barrier to protect the high-value and densely populated west coast of Galveston Bay. The Midbay Barrier leads to a risk reduction of $1,286 million per year and protects 34 thousand people from flooding annually in the current scenario. The upfront cost of this measure is $3,545 million. If the Midbay Barrier is constructed first, it should be in place for at least seven years before the land and storm surge barrier is constructed to get a return on investment. Building the Midbay Barrier after the land and storm surge barrier is ineffective under all scenarios.

The screening results are used to create DAPP maps, which visualise when measures are effective and how measures can be combined. Three DAPP maps were created for the three development scenarios. Figure 2 shows the resulting adaptation pathways for the continued growth development scenario. On the horizontal axis, the climate change scenarios vary from the current scenario to the RCP8.5 scenario. The pathways map shows how the six measures can be combined in time to complement each other. The land barrier, Midbay Barrier, raising houses and buyouts measures are effective on their own throughout their lifetime, which is represented by the continuous line. On the other hand, the storm surge barrier on its own is an ineffective solution, and the Highway I146 levee becomes ineffective after the RCP1.9 climate scenario. For this scenario, eight possible pathways are created based on combinations of the six measures. The costs and benefits of each pathway can quickly be compared using the accompanying table. Because the land barrier and Midbay Barrier are effective in all future scenarios and lead to pathways with a high risk reduction and high benefit-to-cost ratio, these measures are identified as robust measures.



Pathway	Costs Millions $	Benefit Millions $/year	Benefit/ Cost	Protected population Thousands/year
1	7,699	7,264	23.7	160
2	9,259	8,258	22.4	173
3	3,545	3,491	24.7	102
4	12,202	8,325	17.1	180
5	1,909	391	5.1	1
6	725	284	9.8	0
7	2,926	750	6.4	19
8	2,200	750	8.6	19

Table values for the RCP4.5 scenario

Figure 2: The adaptive pathways map and scorecard for the continued growth development scenario (DP1)

The case study has demonstrated how the framework developed for this thesis can generate Dynamic Adaptive Policy Pathways to obtain useful information for policymakers, such as identifying effective, ineffective and robust measures and quantifying the performance of many strategies under many scenarios. The combination of the land and storm surge barrier is the most effective solution to reduce flood risk. On the other hand, the Highway I146 levee is ineffective at reducing flood risk. Furthermore, both the land barrier and the Midbay Barrier have been identified as robust measures and one of both should be implemented as soon as possible. A total of 20 possible pathways are identified and quantified for the Galveston Bay area to account for various climate change and development scenarios.

Thus, the framework developed in this thesis can analyse complex systems in many plausible future scenarios and make the results understandable. Creating a map of the pathways can make the various options clear to the general public, not just hydraulic engineering professionals. Additionally, by quantifying the performance of the pathways, policymakers can have a substantiated discussion of the benefits and disadvantages of the various options. The framework also helps identify robust options early in the process, allowing policymakers to act quickly and limit flood risk. In conclusion, the framework can generate results which help policymakers make informed flood risk management decisions to quickly and effectively reduce local flood risk and protect the population around Galveston Bay.

Disclaimer:

This thesis presents an academic research endeavour and does not serve as an exhaustive design report. It employs a simplified model, cautioning that the inputs utilised herein may not be directly comparable to those in other studies. The costs depicted are notably smaller than those used in related design and feasibility reports. Furthermore, the calculated risk reduction may differ due to varying methodologies, and the model's level of detail is limited. Readers are advised to interpret findings within the context of academic inquiry rather than practical application.

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Nomenclature

Abbreviations

Abbreviation	Definition
ATP	Adaptation Tipping Point
DAPP	Dynamic Adaptive Policy Pathways
DEM	Digital Elevation Model
EMA	Exploratory Modelling and Analysis
	Python Package developed by Jan Kwakkel
FEMA	Federal Emergency Management Agency
FLORES	Flood Risk Reduction Evaluation and Screening
GBPP	Galveston Bay Park Plan
GIS	Geographic Information System
HCFCD	Harris County Flood Control District
HSC	Houston Ship Channel
HUC	Hydrologic Unit Code
IPCC	Intergovernmental Panel on Climate Change
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
PDS	Partial Duration Series
PF	Precipitation Frequency
RCP	Representative Concentration Pathways
RDM	Robust Decision Making
RP	Return Period
RSL	Relative Sea Level
SRTM	Shuttle Radar Topography Mission
SSPEED	Severe Storm Prediction, Education & Evacuation from Disasters
TNRIS	Texas Natural Resources Information System
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WSE	Water Surface Elevation

Definitions

Term	Definition
Flood risk	Probability of flooding multiplied by the consequences of flooding.
Robust design	A design which achieves its goal under many different scenarios and is easily adaptable or expandable to meet its goals.
Scenario	Set of possible future boundary conditions expressed in climate change and development pathways.
Strategy	A combination of measures.

1 Introduction

1.1. Background

The Galveston Bay is a large estuary located on the upper coast of Texas on the Gulf of Mexico. It is home to large areas of sub-tropical marches, as well as essential shipping channels such as the Intracoastal Waterway, running from Massachusetts along the coast to Brownsville, and the Houston Ship Channel, connecting the Port of Houston to the Gulf of Mexico. Roughly 5.4 million people live in the counties surrounding the estuary. Besides its natural value, this area is also a powerhouse for the U.S. economy. The Bay contains 30% of the U.S. crude oil refining capacity and is therefore of vital importance to not only this region but the entire country (USACE, 2021b).

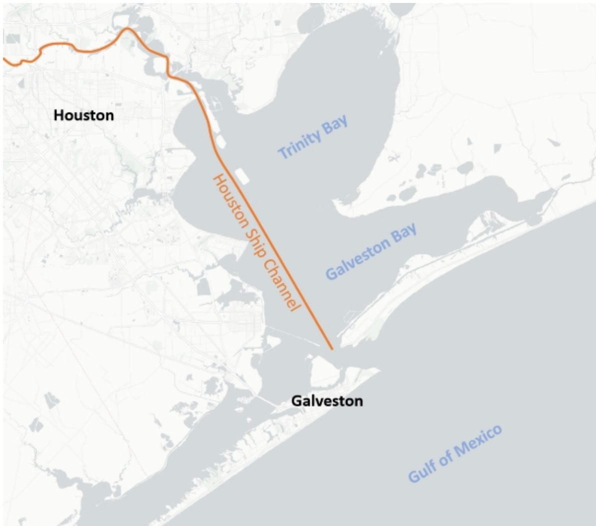


Figure 1.1: Overview of Galveston Bay, OSM (2023)

However, the Gulf Coast has long been tormented by hurricanes originating in the Atlantic. In 1900, the inhabitants of Galveston felt the devastating effects of a hurricane as a category four hurricane landed near the city. This event is known as the Great Galveston hurricane, and to this day, it is still the deadliest (natural) disaster in United States history. This hurricane destroyed at least 3,500 homes and claimed the lives of more than 8,000 people. The Galveston Seawall was constructed in response to this disaster to protect the city from future storm surges (NOAA, 2000). In recent years, the Gulf Coast has been attacked regularly by hurricanes and tropical storms, causing an ever-growing amount of property damage. "The most catastrophic flood events since 2000 include Tropical Storm Allison in 2001, Hurricane Ike (category 4) in 2008, and Hurricane Harvey (category 4) in 2017, which resulted in $5 billion, $28 billion, and $150 billion in damage, respectively" (Sohn et al., 2020).

Several plans have been proposed to protect the Galveston Bay area in response to these devastating hurricanes. The most important proposed concepts are the Ike Dike/Coastal Spine, Galveston Bay Park and Centennial gates (Merrell et al., 2011, Jonkman et al., 2015, Bedient, 2022). These concepts were developed academically by professors and research groups to map out several possibilities. The United States Army Corps of Engineering (USACE) is responsible for coastal protection in the United States and has published a feasibility report in 2021 based on these concepts (USACE, 2021b). In this study, they essentially followed the coastal spine concept.

However, the plan proposed by the USACE in the feasibility report still misses constructive details.

Furthermore, there is still disagreement around what the final design should look like (Ebersole et al., 2021). To be able to make informed decisions, there is a need for a critical comparison of the plans over the entire investment period. Therefore, this thesis aims to inform policymakers, practitioners and stakeholders by constructing dynamic adaptive policy pathways and interpreting the effects of these pathways.

1.2. Problem analysis

The multiple conceptual plans for the protection of the Galveston Bay area show that several alternatives are available for the USACE-designed plan. Currently, no research has been done to analyse what combination of measures included in these plans is the most beneficial for the area. The plans are not mutually exclusive and overlap partially. Therefore, combinations of measures from multiple plans can be created and evaluated. Furthermore, the possible timing of implementing measures in the future is an area where more research is required. Implementing such a complex plan warrants an analysis over the entire investment period. Different solutions might become favourable in the future as hydraulic or societal conditions change, such as the rise of sea levels or increased development in risk-prone areas. By exploring these changes, they can already be taken into account in the design. A design which achieves its objectives in many possible scenarios and can be adapted or expanded if necessary is a robust design.

Currently, policymakers have too little information available which directly compares these plans and measures. To inform policymakers about the potential impact of the proposed plans, it is necessary to quantitatively model the flood risk in the Galveston Bay region. Flood risk is defined in this study as the probability of flooding multiplied by the consequences of flooding. Such a model must include the costs and benefits of the different alternatives for all plausible future scenarios. This model needs to have a short computation time to be able to model many alternatives in many scenarios. However, these requirements raise two problems relevant to this thesis: how to determine the future scenarios considered in the model and how to rapidly model the complex system for these future scenarios?

1.2.1. Modelling many different futures

The uncertainty of the future is a major challenge when trying to find a robust design for a system with a long lifespan. Many natural and socio-economic phenomena influence the probability and the consequences of flooding in the Galveston Bay area. Firstly, the intensity and occurrence of hurricanes can change due to climate change. Secondly, relative sea level rise is the combined effect of sea level rise (National Oceonagraphy Centre, n.d.) and land subsidence. Land subsidence is caused by subsurface hydrocarbon extraction, over-utilisation of aquifers and the weight of buildings (Miller & Shirzaei, 2021). Additionally, the exposure in terms of population and value has seen steady growth. As of 2022, Harris County is the third-most populous county in the United States (United States Census Bureau, 2022), which puts more people at risk of flooding than ever before. Lastly, the increase in population leads to a decrease in wetlands and natural ground cover, which leads to an increase in stormwater runoff and puts more strain on already overflowing creeks and rivers (Sohn et al., 2020).

While some physical effects are mostly understood and predictable within an uncertain range, others, like future land development, are political in nature and, therefore, largely unpredictable. This is the area of '*deep uncertainty'*, which is characterised by unpredictable evolving situations or disagreement between parties about how a system works and its boundaries (Marchau et al., 2019b). Due to this uncertainty of the future conditions, it is almost impossible to design an optimal solution today that will still be optimal in 100 years. Thankfully, Robust Decision Making (RDM) can offer the solution to this problem. RDM focuses on finding an effective design for as many plausible future scenarios as possible. In contrast, conventional design strategies focus on finding an optimal design for the most likely future scenario. Dynamic Adaptive Policy Pathways (DAPP) is an RDM approach which creates strategies for many future scenarios. This approach has been used to provide solutions in a case study similar to the Galveston Bay in Beira, Mozambique (Van Den Broek, 2019).

DAPP is aimed at finding possible solutions to satisfy the design requirements for all plausible futures, also called scenarios. These are further ranked based on scoring criteria, which leads to preferred solutions for all scenarios. Lastly, a pathway is constructed by linking these preferred solutions. By using the DAPP method, it is possible to account for the many different possible futures as well as look at the optimal time to implement measures in the future. This approach has not yet been applied to the Galveston Bay storm surge protection system and could lead to novel insights useful to policymakers.

1.2.2. Rapid modelling of complex hydraulic systems

Analysis and understanding of each individual measure of the proposed plans is especially challenging due to the strong, non-linear connectivity between parts of the proposed measures. Traditionally, storm surge levels of such complex systems have been modelled using sophisticated and resource-intensive numerical modelling software like Delft3D. However, these software programs often require long computation times and detailed parameters, making them less suitable for analysing many different strategies in the early stages of the design process.

Alternatively, rapid flood simulation models are able to capture the essence of these complex systems, are less resource intensive and faster to run, but this comes at the cost of accuracy. These models use simplified mathematical relationships, require less detailed parameters, and have an overall reduced complexity (Jajarmizadeh, 2014). The use of simple models enables quick and informed decisions early on the in design process, when not a lot of information is available. Due to the fast run time, these types of models are required to analyse many different scenarios.

The Flood Risk Reduction Evaluation and Screening (FLORES) model has successfully been used as a rapid flood simulation model in the past. Berchum (2022) has successfully used this model on the Galveston Bay and in Beira, Mozambique. FLORES is also used for this thesis, as it has integrated tools for experimental modelling, and it is fast enough to calculate the many required combinations of scenarios and measures quickly.

1.2.3. Knowledge gap

Information that directly compares the different alternative plans and plan components with the USACE plan is not yet available. Due to the wide range of possible future scenarios, an optimal solution can not be found. However, comparisons can be made for a range of different scenarios. Furthermore, the proposed plans for Galveston Bay have not yet considered the timing of the implementation of their protection measures. Execution of the protection plans is expected to take a considerable amount of time, considering the extremely large scale of the projects. With a significant probability of storm surge flooding each year, the order in which the plans are executed can have a significant impact on the risk incurred during the construction period. Therefore, it is important to not only identify possible solutions but also consider what order of construction is the most beneficial.

1.3. Objective

The objective of this research is to inform local policymakers on a set of solutions for the Galveston Bay area that are effective in many possible future scenarios. Because the state of future conditions is deeply uncertain, robust decision-making is required to formulate a solution or combination of solutions that will work in the future under unpredictably changing circumstances. This can be achieved by applying dynamical adaptive policy pathways to consider many possible future scenarios. A scenario is defined as a set of future hydraulic and socio-economic conditions.

Therefore, the main question of this thesis is formulated as follows:

How can Dynamic Adaptive Policy Pathways support decision-making in the Galveston Bay area?

It is important to divide the main question into several sub-questions to answer such a complex question. The following sub-questions were formulated to help answer the main research question.

I What future scenarios are plausible for the Galveston Bay area?

II Can simple flood simulation models be used to model complex systems?

III What flood risk protection measures can best be applied in the future, and what would be their preferred timing?

IV How can Dynamic Adaptive Policy Pathways be applied to find effective pathways for the future?

1.4. Approach

In order to answer the research questions, flood risk models and methods for decision-making under deep uncertainty have to be compared to find an approach best suited for this thesis. Next, the methodology of the chosen approaches is further elaborated. The flood risk model and chosen exploratory modelling tools are detailed. A framework is set up detailing the methodology of the flood risk modelling and analysis for the case study.
This methodology is then applied to the case study of the Galveston Bay area. The first step of the case study is to analyse the local situation and the proposed flood risk reduction measures. A range of plausible future scenarios for the area have to be identified and quantified based on the literature. Next, various input data have to be collected and preprocessed, ranging from land value and population to elevation data and more. The proposed plans have to be divided into their respective measures and quantified. Lastly, the model has to be validated based on storm surge en water surface elevation data.
The second step of the case study is to execute the screening. The screening calculates the effects of the measures inside the Galveston Bay for the many plausible scenarios. These screening results are used to answer questions from local policymakers and to identify tipping points where measures are no longer effective. Pathways are constructed based on effectiveness regions and PRIM analysis. The case study ends with a summary and evaluation of the most important results of the case. The thesis concludes with a reflection on the case study and recommendations for measures to take. Figure 1.2 gives an overview of the structure of the report.

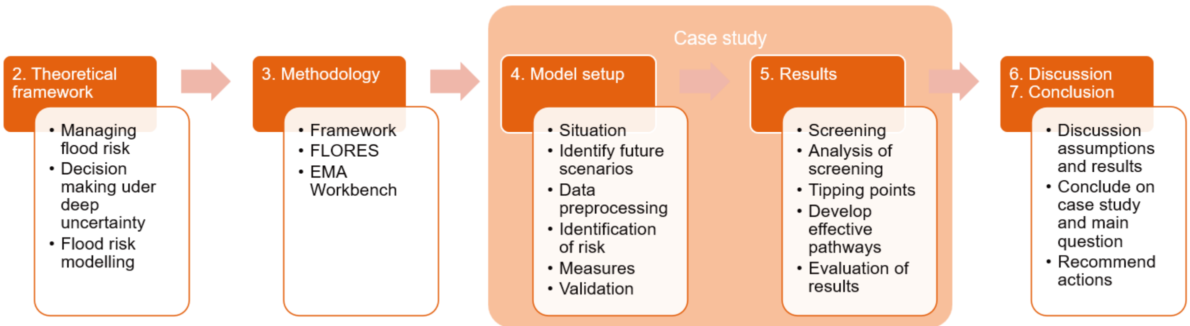


Figure 1.2: Chapter structure of the report

1.4.1. Scope

The computation time of the model is quadratically proportional to the number of measures. Therefore, to keep the total computation time manageable, only a limited number of measures will be considered. Instead, the focus will primarily be modelling many future scenarios and developing the pathways. Rainfall upstream in Harris County is not considered in this thesis. Along with this, Addicks and Barker reservoirs are also left outside of the scope of this research. The effect of pumping stations is also neglected, as their short-term effect is deemed to be low. Storm surge and rainfall are considered independent events in this thesis.

1.5. Reading guide

Chapter 2 provides the theoretical background on flood risk modelling and decision-making under deep uncertainty. Based on the research, Chapter 3 develops a framework. Next, Chapter 4 begins the case study with the FLORES model setup and validation of the model. Chapter 5 evaluates the case study results and uses the Exploratory Modelling and Analysis (EMA) workbench to construct the adaptive pathways and answer local policymakers' questions. Chapter 6 provides a discussion of the used methodology and results. Lastly, Chapter 7 concludes the research and provides recommendations.

2 Theoretical Background

The fields of Flood Risk Management (FRM) and decision-making under deep uncertainty are rapidly evolving. Several approaches are available for modelling flood risk and making decisions under deep uncertainty. Choosing the right approach for the situation depends on many factors, such as the current step in the design process, the time and resources available, the availability of local data, and more. This chapter will elaborate on these approaches and compare them to find the best approach for the Galveston Bay area case study.

2.1. Managing flood risk under uncertainty

Flood risk management has gone through many different design philosophies throughout the years. Traditionally, people built flood protection just above the highest water level they had encountered up till then. In case of a flood, the flood protection would be heightened to the new highest water level, plus a certain freeboard, and this process would be repeated for the next storm. This is an example of a deterministic approach. After the 1953 North Sea Flood, a statistical approach to find the design storm surge levels was chosen, and an extrapolated storm surge level would be the basis for dike design (van Dantzig, 1956). This development led to the introduction of a probabilistic design approach, which bases the level of protection on a storm or set of hydraulic boundary conditions with a specific recurrence interval. An extreme hydrologic event with a 100-year recurrence interval has a 0.01 Annual Exceedance Probability (AEP), thus a 1% probability of occurrence every year (USGS, 2018). The flood defence protection is then designed to withstand this load. An advantage of this method is that the expected rise in sea level for the lifespan of the flood protection measures can be easily included in these boundary conditions. In most of the world (and the Netherlands up until 2017), flood defences are designed in this way.

Since 2017, The Netherlands has used a new standard where the protection level of flood control measures is determined on a risk-based approach (STOWA 2019). The economic and population growth and development of knowledge to better calculate flood risks since the 1960s were the main reasons for updating the previous legal standards, which were based on insights from the period 1953-1960. The revised standards aim to control flood risk at a politically and socially acceptable level of risk. A maximum allowed failure probability is assigned to all flood protection elements based on the risk of failure. Risk of failure is defined as the probability of failure multiplied by the consequence of failure, where the latter is often expressed in economic value and population behind the dike or barrier. This failure probability represents the economic optimum between construction and maintenance costs of the dike and the consequences of failure of the dike (Vrijling, 2001). This maximum allowed failure probability is then divided among the failure mechanisms until each component of the dike has its max allowed failure probability. This probability and the hydraulic boundary conditions then dictate the design of each component.

Using probabilistic methods allowed flood risk experts to quantify uncertainties, approximate changes in future uncertainty, and adjust the design accordingly. However, due to the effects of external factors, such as climate change, economic development or political climate, future boundary conditions for the design can be challenging to determine. Because there is uncertainty about future conditions, many scenarios are possible. This thesis defines a scenario as a combination of (future) hydraulic boundary conditions and (future) socio-economic conditions. *Decision Making under Deep Uncertainty* (DMDU) specialises in dealing with many plausible scenarios (Marchau et al., 2019a) and is further explored in section 2.2. The flood risk modelling has to be performed many times to account for many scenarios and compare many alternative designs. This requires a model with a short computation time, which can run and generate results many times in a reasonable amount of time. Section 2.3 compares several available models and selects the most appropriate model for the case study.

2.2. Decision Making under Deep Uncertainty

Decision-making for the future depends on anticipating change. However, as the world becomes more complex and interwoven, it can be difficult to predict change. The effects of climate change require large and far-reaching societal change, transitions to other energy sources and government intervention. Events like natural disasters, terrorist attacks or societal changes can alter the behaviour of the population drastically. *Deep uncertainty* has been developed as a way to think about these possible future changes. Not by applying a model to predict one most likely future, but a framework to develop all possible future scenarios. According to the Society for decision-making under Deep Uncertainty, ”deep uncertainty exists when parties to a decision do not know, or cannot agree on, the system model that relates action to consequences, the probability distributions to place over the inputs to these models, which consequences to consider and their relative importance.” (DMDU Society, 2023). Lempert et al. (2003) identify three characteristics of deep uncertainty:
”In case of deep uncertainty, the experts do not know, or the parties to a decision cannot agree on:

I The external context of the system
II How the system works and the system boundaries
III The outcomes of interest from the system and/or their relative importance”

The second and third characteristics are most relevant for the Galveston Bay area. Some of the future boundary conditions for the system are deeply uncertain. Parameters such as population development and risk of flooding depend on economic development and local policy changes, both of which can change drastically and unpredictably. Marchau et al. (2019b) use a scale to identify a model’s uncertainty level. Figure 2.1 illustrates these levels of uncertainty. In an ideal world, every system can be modelled using a single (deterministic) model where an estimate can be found for each outcome; this is level 1. In a level 2 uncertainty system, the future can be modelled using a single (stochastic) model, and confidence intervals can be constructed for all outcomes. This level is relevant for well-understood phenomena where some small deviation from an expected value is possible, but the degree of uncertainty is also defined. Probabilistic and statistical tools can be applied to solve level 2 problems. An example of a level 2 problem is deciding which line to join at the supermarket’s checkout. Multiple alternative system models are possible for level 3; however, the range of outcomes is still limited. Only a few plausible futures exist. An example is sea level rise: several alternate futures can be modelled for the expected sea level rise. Lastly, level 4 is the area of deep uncertainty, which is subdivided into two categories. Level 4a gives many plausible futures using many alternative system models, which produce a wide range of outcomes. Examples of level 4a uncertainties in the Galveston Bay area are the development in the region and the effects of climate change on hurricanes. Level 4b is entirely unknown: the system model, outcomes, and futures are all unknown. As level 4a is most relevant for the case study, DMDU approaches can be applied to the case study.

2.2.1. Robust Decision Making

Robust Decision Making (RDM) is an analytical framework to help identify, characterise and evaluate decisions and strategies for situations characterised by deep uncertainty (Lempert, 2019). Traditionally, decision-making has been based on finding the optimal solution for the problem that is most likely to occur or perhaps a characteristic situation or load based on a probabilistic analysis. This approach of modelling and decision-making corresponds to level 2 and 3 uncertainty of Figure 2.1. Compared to traditional, utility-based decision-making, there are two main differences with RDM. Firstly, it characterises the future as many plausible futures with, in some cases, unknown probabilities of occurring.

	Complete determinism	Level 1	Level 2	Level 3	Level 4 (deep uncertainty)		Total ignorance
					Level 4a	Level 4b	
Context (X)		A clear enough future	Alternate futures (with probabilities)	A few plausible futures	Many plausible futures	Unknown future	
System model (R)		A single (deterministic) system model	A single (stochastic) system model	A few alternative system models	Many alternative system models	Unknown system model; know we don't know	
System outcomes (O)		A point estimate for each outcome	A confidence interval for each outcome	A limited range of outcomes	A wide range of outcomes	Unknown outcomes; know we don't know	
Weights (W)		A single set of weights	Several sets of weights, with a probability attached to each set	A limited range weights	A wide range of weights	Unknown weights; know we don't know	

Figure 2.1: Levels of uncertainty (Marchau et al., 2019b)

This characterisation generates many sets of differing boundary conditions called scenarios. Secondly, alternative options are compared based on robustness instead of optimality. Robustness can be expressed as the ability to work sufficiently in as many possible futures as possible, trading a small amount of optimum performance for less sensitivity to broken assumptions or by keeping many options open (Lempert & Collins, 2007).

For example, when applying RDM to a system, the behaviour of the system is considered for many different possible future scenarios. The effect of short-term solutions is then evaluated. If a strategy works well for many scenarios, it is called a robust strategy. A robust strategy is one that performs well, compared to the alternatives, over a wide range of plausible futures (Lempert et al., 2003). Other definitions exist, such as keeping options open(Rosenhead, 1990). This focus on robustness is in contrast to traditional design methods, which would try to find an optimal long-term solution for a most likely future. Robust decision methods seem most appropriate under three conditions:

- when the uncertainty is deep as opposed to well-characterised,
- when there is a rich set of decision options,
- when the decision challenge is sufficiently complex, decision-makers need simulation models to trace the potential consequences of their actions in many plausible scenarios.

RMD is a general approach for dealing with deep uncertainty in decision-making. Dynamic Adaptive Planning (DAP) is an approach that focuses on implementing an initial plan prior to resolving all major uncertainties, with the plan being adapted over time as more information becomes available (Marchau et al., 2019b). Lastly, Dynamic Adaptive Policy Pathways (DAPP) explicitly considers the timing of actions. The DAPP approach is the most suitable for this thesis, as the timing of implementing the actions is one of the research questions.

2.2.2. Dynamic Adaptive Policy Pathways

Haasnoot (2013) introduced the concept of Dynamic Adaptive Policy Pathways (DAPP) first in 2013. This approach aims to build flexibility into a flood risk mitigation plan by sequencing the implementation of measures over time so that the system can be adapted to changing conditions (Haasnoot et al., 2019). Alternative sequences are developed a priori and can be used to deal with a range of possible future conditions.

The approach starts from the premise that measures have a design life and might fail when operating conditions change (Kwadijk et al., 2010). Once a measure fails to make the system meet its required objectives, one or multiple measures must be applied to meet the objectives. As time passes, this might repeat itself, and thus, pathways start forming. The approach is divided into seven distinct steps, which are briefly explained below.

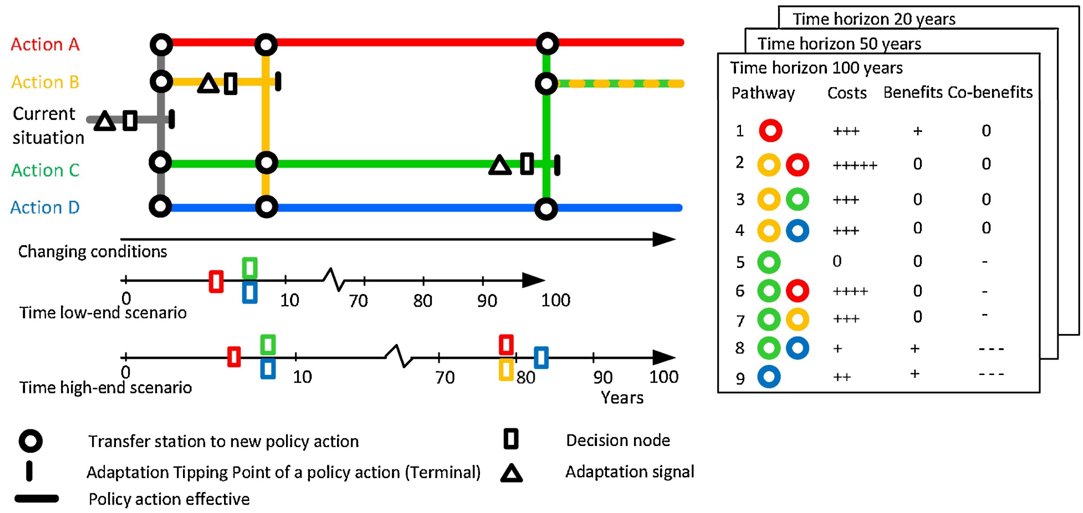


Figure 2.2: An example of an Adaptation Pathways Map (left) and benefit-cost scorecard (right) (Haasnoot et al., 2018)

Step 1: system definition
In the first step of the approach, the system and its characteristics, objectives and constraints must be described. Its objectives, or conditions for success, should be formulated in terms of indicators and targets. These are then evaluated for all future scenarios to determine when Adaptation Tipping Points (ATPs) are reached, and measures are required to achieve the system objective. An ATP is a time when a measure that successfully achieved the system objective is no longer sufficient due to changing hydraulic or socio-economic conditions.

Step 2: assessment of system vulnerabilities and opportunities, identification of ATP's
In the second step, the reference design is tested against all the plausible futures. A tipping point is reached when the design's performance becomes unacceptable. Each plausible future is defined as a scenario.

Step 3: identification of interventions and their ATP's
During the third step of the approach, the possible measures that address the vulnerabilities found in step 2 are identified. A list of possible effective measures should be constructed for each plausible future scenario, and the tipping points of these measures should also be identified.

Step 4: design and evaluation of pathways
Now, the actual pathways can be constructed for all scenarios. Pathways can be a combination of measures and change over time, as some measures might become ineffective over time or only effective after a certain time. Then, these pathways can be evaluated based on the scoring criteria such as costs, safety, environmental impact, or others. Figure 2.2 gives an example of an Adaptation Pathways Map. Initially, all measures are effective at achieving the required results; however, after approximately eight years, Action B becomes ineffective, and its Adaptation Tipping Point is reached. From this time forward, policymakers should switch to a different measure. Then, after a long time, Action C becomes ineffective as well. However, a combination of measures B and C would be effective. Meanwhile, measures A and D are effective over the entire time span, but these might be unwanted for different reasons like high costs or unwanted secondary effects.

Step 5: design of the adaptive strategy
In this step of the approach, the preferred pathways are selected and further expanded based on the evaluation and scoring of the previous step. The initial measures and long-term options are selected. A monitoring system is established that can track the important signals to identify upcoming tipping points. A well-designed monitoring system should provide a warning ahead of an ATP, with sufficient time to decide which measure to take and implement the measure before the ATP is reached.

Step 6: implementation of the flood mitigation plan
At this point in the process, it is time to start building or otherwise implementing the first required measures of the flood mitigation plan. The status quo is often not desirable, and thus, most, if not all, pathways start with some immediate measure. After these initial measures are taken, the objectives identified in step 1 should be achieved, and the monitoring system should be implemented.

Step 7: monitoring of the strategy
Lastly, as time passes, the signpost information is collected and compared to the previously identified tipping points. If a parameter reaches the beforehand determined value, measures can be started, stopped, altered, or expanded as required by the pathway. This phase should be as simple as following one of the predetermined pathways. However, if the system changes in ways not accounted for by any of the pathways, it can become necessary to analyse the system again and construct new pathways based on the boundary conditions.

2.2.3. Use of DAPP in Hydraulic Engineering

In recent years, DAPP has been applied in practice in the Dutch Delta Program under the name of Adaptive Delta Management (ADM). The Delta Program (2014) uses the ADM approach to develop common-sense measures to deal with uncertainties by linking short-term decisions with options for adaptation in the future. One of the key reasons to choose this approach is to better anticipate events to accomplish future measures in a more cost-effective or straightforward manner and to prevent measures from becoming obsolete in the future if a pathway is chosen which makes certain solution strategies impossible (STOWA, 2017). Four different future scenarios are defined in the Delta Program; these are called the Delta Scenarios. The scenarios are based on climate change and socio-economic development: *Busy, Steam, Rest, Warm*. Insights from ADM have been used in several sub-programmes, such as Southwest Delta, Rivers, Coast, and Wadden (STOWA, 2017). In the IJsselmeer region, this has led to flexible water surface level management, increasing available water. By using ADM, they expect to meet the region's water needs until 2050 and keep the option open to increase the amount of available water. Some of the main knowledge gaps concern determining tipping points and identifying measures and adaptation pathways in relation to climate change.

Furthermore, the use of DAPP has become increasingly popular in academic research. Van den Broek (2019) successfully implemented this approach for a coastal flood protection case study in Beira, Mozambique. Several possible measures were analysed for a spectrum of plausible future scenarios. Van den Broek found several benefits in using the DAPP approach. Firstly, while the adaptation pathways image can be challenging to interpret initially, it becomes a clear visual representation of the required measures over different futures. This ability to visualise results is an essential benefit of DAPP for this thesis as well, as the goal is to inform policymakers. Secondly, the adaptation pathways image can be helpful to locate possible lock-ins and thus prevent these. Lastly, by sequencing measures, the more expensive options can be taken later, while the early measures consist of less expensive options. However, Van den Broek (2019) also notes some limitations of the approach; for example, the analysis of a case can be a time-consuming and complex endeavour.

Later, Vrinds (2021) applied the DAPP approach to develop an adaptive flood defence system in the Rhine-Meuse estuary. Vrinds (2021) notes it could provide valuable insights into alternative design methods which can handle uncertainties following climate change. Next, Trommelen (2022) incorporated the DAPP approach into a framework capable of creating adaptation pathways and evaluating these with an incorporated scenario-based economic evaluation. This framework was then applied successfully to a fictive case and a case in Singapore. Trommelen (2022) underwrites the advantage of the DAPP approach to easily evaluate all possible scenarios. Furthermore, it is noted that the case outcome is sensitive to a changing discount rate and socio-economic growth rate. Therefore, it can be beneficial to consider these as an uncertainty.

Bodelier (2023) has reviewed recent studies on hydraulic structures and their use of the Adaptation Pathways method. Four of the six reviewed studies used the method to extend the service life of already existing structures. Most of these studies use the costs of measures as the main criterion for evaluating pathways. However, other criteria such as hindrance to port activity (Rowbottom, 2021), hindrance to the system (Vrinds, 2021), compatibility, sustainability and durability are also used. One of the review's main findings is that generalisation of the used approach for similar hydraulic structures is often not possible. Rowbottom (2021) shows that different paths are preferred for two port case studies where the same approach was applied with corresponding proposed measures. Several authors mention that local conditions significantly impact the preferred path. Therefore, making a generalised pathway for similar structures is impossible due to the varying local conditions (Rowbottom, 2021) (Hogeveen, 2021). These conclusions highlight the importance of correctly assessing the local conditions to obtain reliable results when using the DAPP approach.

In conclusion, applying DAPP for flood risk management offers several strengths. Firstly, it provides a clear visual representation of the necessary measures across various future scenarios. This visualisation enables decision-makers to better understand the measures required for effective flood management. Additionally, DAPP facilitates the identification of robust short-term measures that result in a lower overall cost. However, there are also weaknesses associated with DAPP. One such weakness is the need to analyse a large number of measures across multiple scenarios, which can be time-consuming and resource-intensive. Another weakness lies in the sensitivity of the model to changes in discount rates. Nonetheless, this sensitivity can be viewed as an opportunity when incorporating multiple discount rate values as uncertainties in the model, which allows for a more comprehensive analysis of potential outcomes. Another opportunity is the inclusion of not only monetary value as a scoring condition but also other factors, such as hindrance to port activity, affected population, or ecological impact. By considering a broader range of criteria, decision-makers can make more informed decisions.

2.2.4. Quantifying Robust Decision Making

One of the main challenges for RDM, or analyses that rely on Deep Uncertainty as a whole, is that the effects of many decisions and scenarios must be quantified. Exploratory modelling and Analysis (EMA) is a research methodology that uses computational experiments to analyse complex and uncertain systems (Bankes, 1993). Exploratory modelling offers computational decision support for decision-making under deep uncertainty and Robust Decision Making (Kwakkel, 2023).

Exploratory Modelling (EM) is a tool to explore a wide variety of scenarios, alternative model structures, and alternative value systems based on computational experiments (Bankes, 1993). A computational experiment is a single realisation of the given model under a set of parameters. It reveals how the real world would behave if the various hypotheses presented by the structure and the parameterisation were correct. By exploring many of these hypotheses, one can get insights into how the system would behave under a large variety of assumptions (Bankes et al., 2013).

EMA can be useful when relevant information exists that can be exploited by using models, but where this information is insufficient to specify a single model that accurately describes system behaviour. A single model run drawn from this potentially infinite set of plausible models is not a "prediction"; instead, it provides a computational experiment that reveals how the world would behave if the various guesses any particular model makes about the various unresolvable uncertainties were correct. EMA is the explicit representation of the set of plausible models, the process of exploiting the information contained in such a set through a large number of computational experiments, and the analysis of the results of these experiments (Bankes et al., 2013).

EMA usually generates a large number of results based on a large number of model runs. These results have to be analysed and visualised in a way that best communicates to decision-makers. The goal is not to find a single best strategy given a system model but to display the system's behaviour over the uncertainty space. Algorithms such as the Patient Rule Induction Method (PRIM) or Classification and Regression Trees (CART) can be used to identify these patterns in a database of model results.

EMA has been proven to be a very powerful approach for discovering robust decisions or strategies, especially through the use of adaptivity (Bankes et al., 2013). Adaptive strategies aim to allow immediate implementation before all major uncertainties have been resolved. This is done by adapting the strategy over time as new knowledge becomes available. Immediate measures make commitments that can shape the future while preserving the required flexibility.

2.3. Flood risk modelling

Many high-end flood simulation models have been developed (e.g. SWMM, Delft3D, HEC-RAS, and MIKE) as the available computation power has continued to increase. However, these high-end models are not the best choice for every situation. A more conceptual model might be more appropriate early in the design process when information and budget are limited or when trying to optimise for a single aspect. Due to the different needs and requirements for these models, a whole spectrum of models has been developed, which differ in their level of spatial detail. Broadly speaking, these models can be divided into three categories:

1. Conceptual risk optimisation models
2. Detailed risk simulation models
3. Flood risk screening models

Figure 2.3 illustrates the main differences between these models. They are discussed in more detail in the following sections. This section ends with a reflection on which model is most appropriate for this thesis.

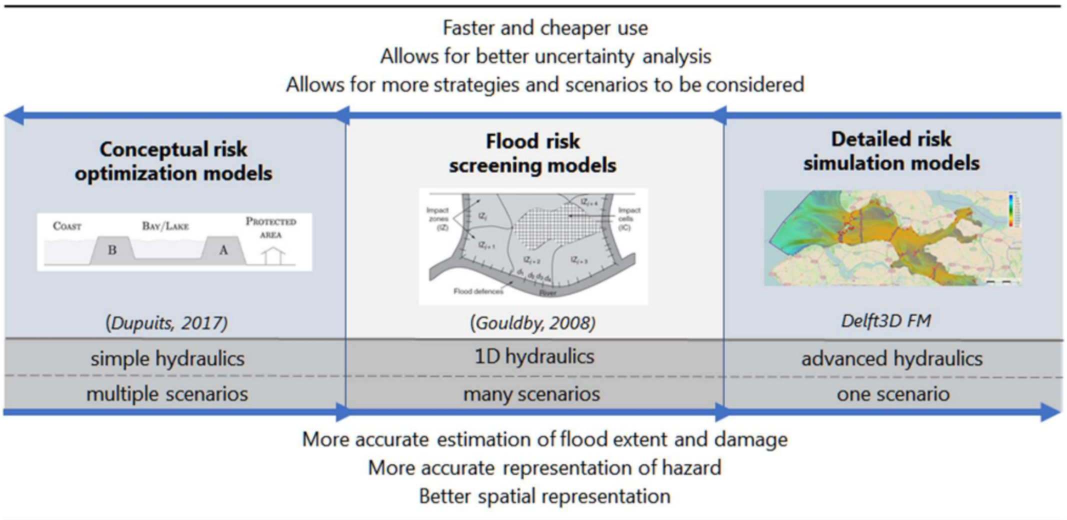


Figure 2.3: Comparison of flood risk models (Van Berchum, 2019)

2.3.1. Available flood risk models

Conceptual risk optimisation models

The most schematised are the conceptual risk optimisation models, which focus on one hydraulic process or influence and have a highly simplified spatial model (Dupuits et al., 2017). These models only need generalised hydraulic boundary conditions and limited land value numbers. As a result, the outputs are also generalised and will miss much of the nuance that more detailed modelling offers. Calculation times of these models are usually extremely short, in the order of fractions of seconds. The advantage of these models is the high-speed calculations, which allow many strategies and scenarios to be considered. The rapid calculation speed also enables uncertainty analysis and risk optimisation. However, the downsides are simplified estimates of flood damages and often no spatial representation of the damages. Conceptual risk optimisation models can be beneficial in a preliminary design stage, where simplifications can be used to obtain rough estimates quickly or later in the design process to optimise the system for one aspect.

Detailed risk simulation models

At the other end of the spectrum are highly detailed risk simulation models such as Delft3D (developed by Deltares), MIKE (developed by DHI) or HEC-RAS (developed by the USACE) used by Baky (2020), Nigussie (2019) and Farooq (2019) respectively. They are widely used due to their relatively accurate simulations, even for large areas. However, these complex models require extensive data on hydraulic boundary conditions, elevation data, spatial land value, and population data. This complexity makes these models time-consuming and expensive to set up. Also, due to the high complexity, the run time of a single simulation can become very long, which makes considering many strategies and scenarios impossible. Detailed risk simulation models are often used only in the detailed design phases or to make a more informed decision when comparing two or three alternatives in the design process. Also, when the hydraulic boundary conditions are unknown, it can take considerable effort and a long time to accurately identify these conditions.

Flood risk screening models
Flood risk screening models cover the middle ground between these two approaches. Screening models try to capture the spatial level of detail and granularity of the detailed risk simulation models while getting as close to the calculation times of the conceptual risk optimisation models as possible by simplifying the schematisation of the project area. On the one hand, they should be simple enough to run without detailed hydraulic boundary conditions and fast enough so that many scenarios and alternatives. On the other hand, they should be detailed enough to model reality (sufficiently) accurately and provide accurate information on the effects and damages of flooding. The balance between computation speed and level of detail must be found.

2.3.2. Review of flood risk models

The flood risk screening models are best suited for this research because robust design methods require the modelling of many different possible futures. Whereas detailed models can predict damages and risks more accurately, the computation time quickly becomes too high to perform more than a handful of runs. On the contrary, the conceptual risk optimisation models can run millions of times in a short time frame, which is required for robust design methods. However, they lack the detail needed to represent the flood hazard accurately and can lack the complexity necessary to model all proposed measures.

Only a few widely applicable flood risk screening models have been developed. A recent addition is the FastFlood model, developed at the University of Twente (van den Bout et al., 2023). This model is 1500 times faster than traditional flood depth computer models while retaining an accuracy of 97%. However, the computation time shows quadratic growth proportional to the area as it uses pixels to model flood height. The Galveston Bay area is quite large, which quickly leads to far too long computation times.

The Flood Risk Reduction Evaluation and Screening, or FLORES, model has been developed by Delft University of Technology and the World Bank (van Berchum et al., 2018). It solves this problem by using basins and contours as its smallest unit. These are considerably larger than the pixels used in the FastFlood model, which keeps the computation times short and also for large areas. Therefore, FLORES was chosen as the flood risk screening model for this research. A first version of the model was applied to the Galveston Bay case (van Berchum et al., 2018). However, this version of the model was limited in capability and did not include pluvial flooding, for example. Next, an improved model version was applied in a case study in Beira, Mozambique (van Berchum et al., 2020) to demonstrate the enhanced model. Lastly, Van den Broek (2019) used the model for a case study in Beira, with an extensive application of exploratory modelling resulting in a system of dynamic adaptive policy pathways. The workings of the model are further explained in Chapter 3.

3 Method

The main objective of this thesis is to inform policymakers of the effects of implementing various (combinations of) flood risk reduction measures under many plausible but uncertain futures. This information consists of trade-offs, dead pathways and visualisations of monitoring plans. These are created using a combination of innovative methods. First, Section 3.1 explains the general framework developed in this thesis to obtain this information. Secondly, Section 3.2 describes how the flood risk model works. Lastly, Section 3.4 covers the analysis methods used to interpret the flood risk results.

3.1. Framework

Figure 3.1 shows the framework developed for this thesis. This framework aims to obtain valuable information to policymakers, and this framework is implemented in the case study of Chapter 4 and 5. The first step of the framework is to analyse the study area, collect necessary input data for the FLORES model and perform any required data preprocessing. The model requires elevation, storm surge, rainfall, population, development, uncertainty data, and more. The second step is to set up the model for the study area. This step identifies the most risk-prone areas, and flood protection or mitigation measures are defined. The third step of the framework is to validate the results of the hydraulic modelling using historical data or other more detailed hydraulic models. The effect of measures should also be validated in this step.

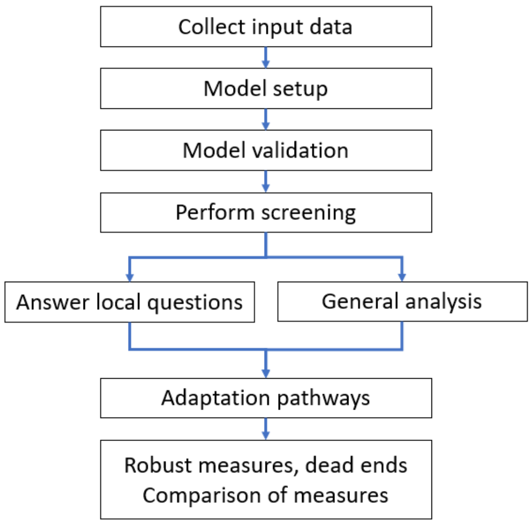


Figure 3.1: Overview of the framework developed for the thesis

After the model setup and validation are completed, the full flood risk screening is performed. The screening repeats the flood simulation for each combination of measures, future scenarios and hydraulic boundary conditions. The results of the screening are used in two ways. Firstly, questions from local policymakers are answered based on directed analyses of the results. Secondly, a broad analysis is performed on the entire result set to find interesting system behaviour, identify tipping points and establish effectiveness regions. Lastly, based on the analysis of the screening results, the dynamic adaptive policy pathways themselves are constructed. Based on the pathways map, policymakers can be informed on robust measures, dead ends, and the effects of uncertainties on the system and compare strategies in different future scenarios.

3.2. Flood Risk Model

The Flood Risk Reduction Evaluation and Screening model, or FLORES, is a generally applicable decision-support model for the early planning stages of flood risk management (van Berchum, 2022). The model can explore and evaluate many different measures and strategies in a wide range of plausible scenarios in a region at risk of flooding. The main characteristics of the model are:

1. enable a risk-based assessment of flood risk reduction strategies
2. low computation time per simulation
3. consider both structural and non-structural measures
4. use multiple performance indicators to compare strategies
5. be applicable to a wide range of regional layouts.

FLORES consists of two parts: a flood simulation model and an analysis toolbox. Incorporation of the EMA workbench provides a set of exploratory modelling and analysis tools. The flood simulation model can calculate flood levels and provide a damage estimate based on the flooded property. The flood simulation is done for one specific set of hydraulic boundary conditions and one risk reduction strategy. The EMA workbench can run this flood simulation model for a wide range of possible scenarios and measures and manages the results. Tools provided by the EMA workbench support the interpretation of the large dataset of results and lead to the creation of pathways. The tools are further elaborated in Section 3.4. Figure 3.2 provides a high-level overview of the structure of the model.

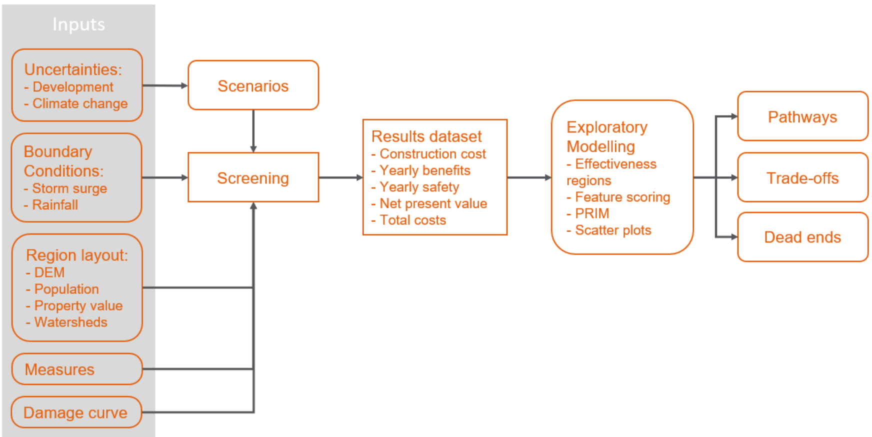


Figure 3.2: High-level overview of the FLORES model

3.3. Flood simulation model

Figure 3.3 shows an overview of the schematisation of a flood event simulation in FLORES. On the left side of the figure, the four model inputs can be seen. These are the flood risk reduction strategy, region layout, hydraulic boundary conditions and the effect of the uncertainties. FLORES uses these inputs to run the flood simulation model, which determines the maximum water surface elevation (WSE) due to the combination of rainfall and storm surge. Next the impact calculations are performed based on the maximum WSE, depth-damage curves, property value, and population data. Damages and number of affected people are calculated. Combined with the construction costs of the measure, the effectiveness of the measure can be determined. This is returned as the output of the simulation and discussed later on.

To understand the model, it is important to understand how a region is schematised for the model. First, the study area is divided into basins based on watersheds. Next, these basins are subdivided into contours of equal elevation every 25 cm. These contours are the fundamental units of the FLORES model. Every contour has a monetary value and population number coupled to it based on GIS data. Inundation levels are calculated per contour, and measures can be applied on a contour level. This means the model results are also generated per contour, which allows us to spatially identify the areas where a measure is most effective.

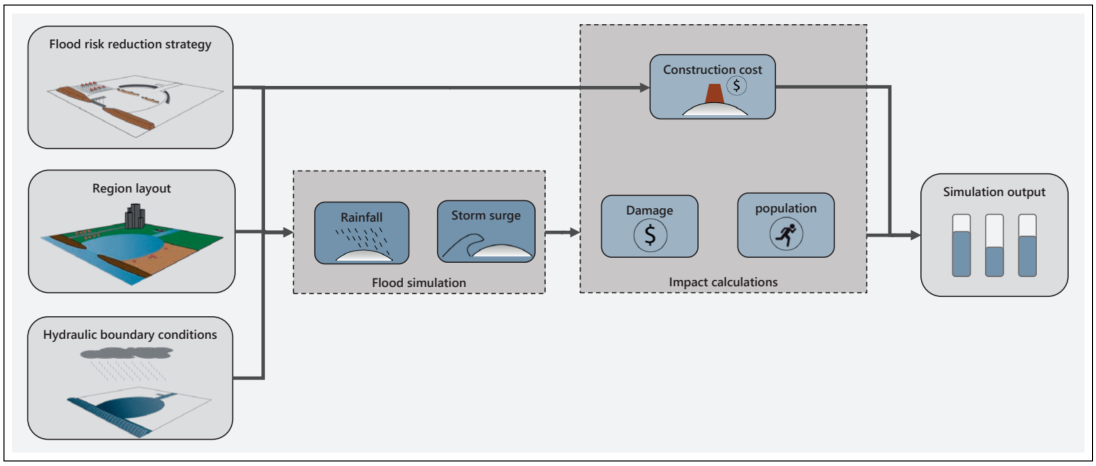


Figure 3.3: The schematisation of a flood event simulation in FLORES (van Berchum, 2022)

3.3.1. Model inputs

Several types of input data a required to run the model. Some are large geospatial datasets, which are often publicly available, and others are defined by the user based on proposed measures, for example. The required input data is divided into three categories: *Region layout, Flood risk reduction strategies and Hydraulic boundary conditions*. The following input is required for the model:

- Region layout
  - Digital Elevation Map: elevation data of the project area, more granular is better
  - Population data: population data of the project area, more granular is better
  - Land or property value data: parcel-based property value if available otherwise more general land value data
  - Watershed data: identification of borders of watersheds
- Flood risk reduction measures
  - Structural measures: location, height, length, width, constant costs, variable costs, protected area
  - Drainage measures: location, constant costs
  - Retention measures: location, new retention capacity, constant costs, variable costs
  - Emergency measures: location, evacuation factor, constant costs
- Hydraulic boundary conditions
  - Storm surge data: storm duration, storm return period, water surface elevation, wave height, wind velocity and wind direction
  - Rainfall data: storm duration, storm return period, precipitation levels
- Uncertainties:
  - Development: future industrial and population developments
  - Climate change: future sea level rise and storm and rainfall intensity

Region layout
The first type of model input data is the region layout. The first step in creating the region layout is to define the study area boundaries by using a digital elevation map (DEM) of the region. These are publicly available worldwide at a low resolution, although higher-resolution data, such as LIDAR data, can also be used when available within the project. The lower-resolution worldwide DEMs are especially well-suited for projects where time and resources are limited because an extensive period of data collection is not required. Using GIS tools, watersheds can be defined based on a DEM when

they are not defined yet by local authorities. In the model, these watersheds are called drainage basins, which are areas where all water drains towards the same place. Next, the DEM is used again to divide each basin into contours of equal elevation for a set height. It is important to find a balance in the step size between contours: large height increments can lead to generalisation and a loss of resolution, but a small step size can lead to strange contours due to noise in the DEM. Model computation time is not significantly affected by an increase in the number of contours. Based on the contour elevations and areas, the model constructs volume-depth curves for each basin. Figure 3.4 shows this process of schematisation of the study area.

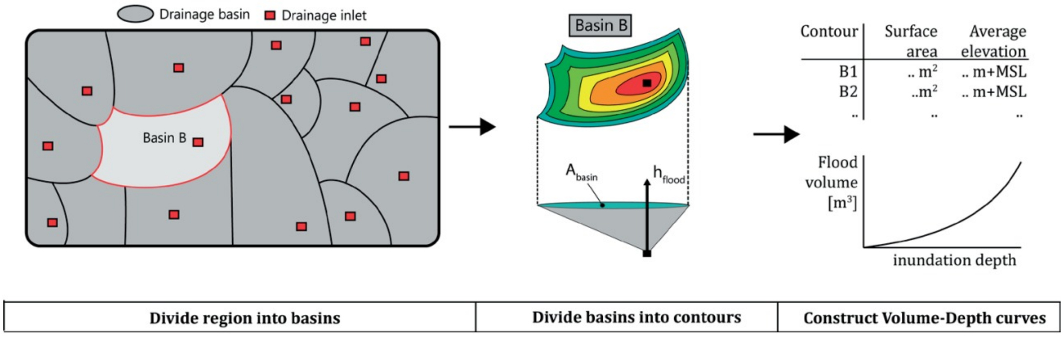


Figure 3.4: Schematised process of the area of interest based on DEM data (van Berchum, 2022)

With the basins and contours defined, the population numbers and land value data can be added to the contours with GIS software. Using more detailed information in this step will lead to better final results. In the United States, property information on a parcel level is available from local appraisal districts. Preferably with development category information such as residential, commercial or industrial. However, when such detailed information is unavailable, a more generalised land use map with average land value data can also be used. For the population data, this process is similar. The highest resolution data is preferred in this step as the outcomes will be more accurate. Due to the way the model is set up, higher resolution data does not add to the computation time of the model; only increasing the number of basins or contours increases the computation time. A more general average density based on total population estimates can also be used if this is unavailable. Lastly, this information is summarised for each contour so that each contour has a population number and a total value per development category.

Flood risk reduction measures

The second type of model input data is the flood risk reduction measures. This data comes in the form of a list of possible measures that can be implemented to either mitigate or reduce the flood risk. A wide range of measures is possible: levees, storm surge barriers, house raising, retention improvements, infiltration improvements, construction of channels and more. The measures which can be applied depend on local conditions, both physical and political. Some measures might not be technically feasible due to local geography or hydraulic conditions, while other measures might not be politically feasible due to lack of support or lack of funding. Based on these local conditions, an engineer can list possible measures to consider for the area of interest. This list contains information about the structure, which will be used later on in the flood simulation and damage calculations modules. Some of the information required is levee height, levee length, construction cost per km length and m height, variable and fixed costs, retention capacity, barrier height and more. As this approach is focused on the early stages of design, it is important to quickly choose some key figures for the costs to be able to keep progressing.

Hydraulic boundary conditions

The third type of model input data is the hydraulic boundary conditions. FLORES uses rainfall and storm surge levels during a storm event as hydraulic boundary conditions to calculate the flooding in the area of interest. Rainfall is defined as precipitation in mm/hour across all basins simultaneously for a given storm duration. The storm is defined by a water surface elevation, wave height, wind velocity and wind direction for the duration of a storm. These conditions are applied at the edge of basins that border the open sea but can also be applied to specific basins if required.

To better represent the effectiveness of the measures for different categories of storms, the model uses risk curves. This is further explained in Section 3.3.5. Hydraulic boundary conditions for several storms of various return periods are required as input to construct this risk curve. For example, a set of return periods such as 10, 50, 100, 500 and 1000 years can be used.

Uncertainties
Lastly, uncertainties pertaining to future conditions are required as input for the model. Future development and climate change aspects are included in the model as ranges. The model uses one value within the predefined range for each flood simulation event. The combination of these uncertainties is called a scenario. Then, the boundary conditions are adapted to this specific future scenario, and the flood simulation model can be run with the adapted boundary conditions.

3.3.2. Modelling measures

Various measures can be taken to reduce the risk of flooding in an area. Some are aimed at reducing the probability of flooding, while others are aimed at reducing the consequences of flooding. This section explains the main types of measures and how they are modelled. Structural measures like dikes and storm surge barriers are modelled as a line between two basins. The measure is characterised by length, height, slope, and Iribarren number. The model will also calculate for each time step if overtopping or overflow of the structural measure occurs and if the measure fails. Drainage measures improve a basin's drainage capacity and link it with an outflow basin directly. Retention measures change the total retention capacity of a basin. Emergency measures affect the evacuation rate in a basin. A higher evacuation rate decreases the total population of a basin when a storm makes landfall. Elevating structures shifts the depth-damage curve applied to a basin, which leads to a lower damage number for the same inundation level. Buyouts and preventing settlements lower the total value and population in a basin. Lastly, land raising increases the height of contours.

3.3.3. Flood simulation

Inside this module, a hydrological balance is performed for each basin and each time step for the entire duration of the storm. The program will save each basin's highest water surface elevation during the storm event. The hydrological balance is calculated using the following formula from Berchum (2022):

$$V_i = V_{i-1} + (Q_{r,i} + Q_{s,i} + Q_{fi,i} + Q_{di,i} - Q_{in,i} - Q_{rt,i} - Q_{do,i} - Q_{fo,i}) \cdot t \tag{3.1}$$

The volume of water in a drainage basin after time step i (V_i) depends on the volume at the previous time step (V_{i-1}), the length of the time step (t), and several hydrological processes that cause an in or outflow of water. Inflows are rainfall (Q_r), storm surge overtopping nearby barriers (Q_s), surface flow from neighbouring basins (Q_{fi}), and drainage of upstream basins (Q_{di}). Outflows are infiltration (Q_{in}), drainage flow (Q_{do}), and surface flow towards neighbouring basins (Q_{fo}). The difference between inflow and outflow is stored in the basin (Q_{rt}), starting with retention. When the retention capacity is fully utilised, water floods the streets, starting at the lowest part (often the drainage point) of the basin (van Berchum, 2022). Figure 3.5 shows the inflow and outflows.

The interfaces between land and water and between basins are schematised as lines separating the basin from the water outside. Structural measures, such as levees, storm surge barriers, dunes, etc., can be applied to these lines. The model uses basic formulas to calculate the amount of water overflowing or overtopping a barrier. The overflow and overtopping are then inflows into the basin behind the barrier. Fragility curves incorporate the risk of complete failure of a flood defence measure, as the impact of failure is extremely large.

Figure 3.6 shows a schematic example of the flood simulation's results. The hydrological balance of basins A and B is calculated at each time step. Basin B sees flooding due to the storm surge on the ocean. Each contour within basin B has its own height; therefore, not all contours experience inundation.

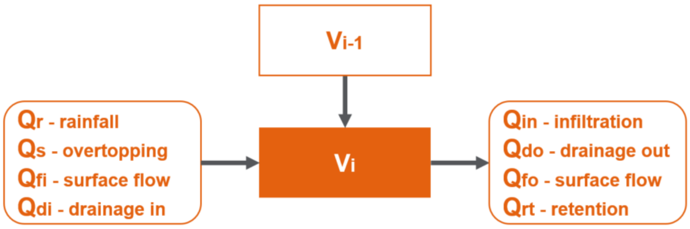


Figure 3.5: Schematisation of the hydrological balance executed at every time step

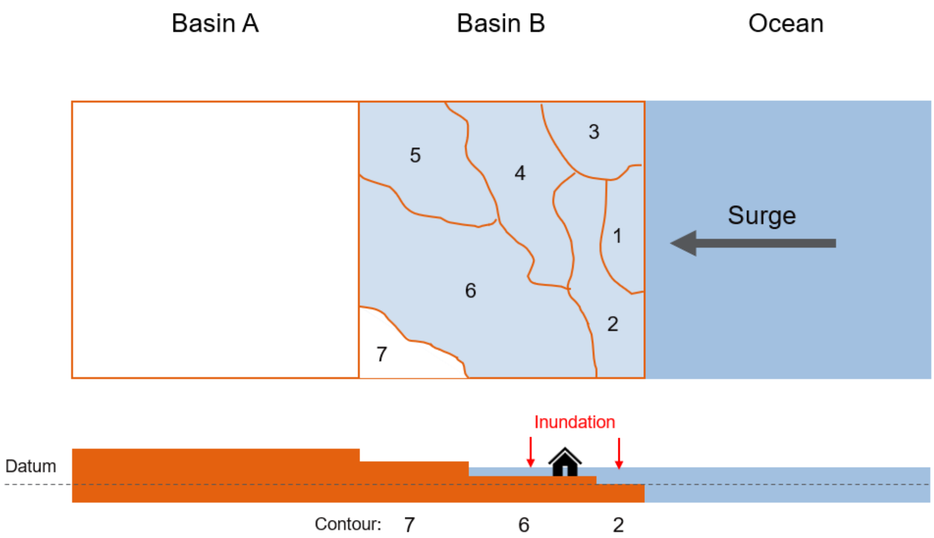


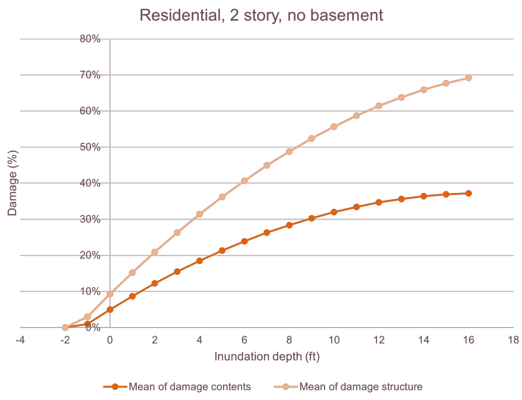
Figure 3.6: Example of a storm surge causing flooding in basin B and various levels of inundation in the contours of basin B.

During the flood simulation, the highest level of inundation per contour is saved and used in the impact calculation.

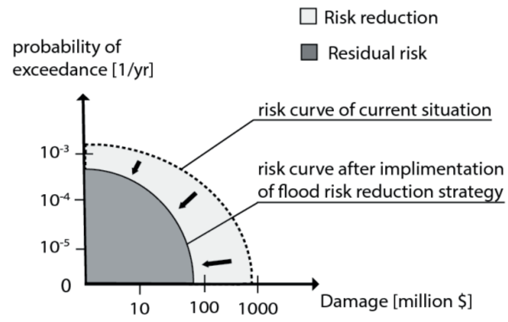
3.3.4. Impact calculations

Three metrics are calculated as part of the impact calculation: the damage in dollars, the number of people affected and the costs of new construction and repair of the flood protection measures. The total damage in dollars is calculated by applying depth-damages curves defined in the Coastal Texas study from the USACE (2021a). A depth-damage curve specifies, for one category of development (residential, commercial, industrial, etc.), what the damage is to the structure and the contents as a proportion of the total value. This damage proportion is defined for all levels of inundation. An example of such a curve can be seen in Figure 3.7a. The highest water surface elevation per basin during the storm was recorded during the flood simulation. Inundation levels are determined by subtracting the average height of each contour from the recorded maximum water surface elevation. The model will calculate the damage for each contour by multiplying the total value in the contour with the appropriate damage percentage given the level of inundation for each type of development. These damage numbers are summed over all contours per basin and, secondly, over all basins to get the total damage over the entire area.

The total number of affected people is also determined by summing up over all the contours. People are considered affected when the inundation in a given contour exceeds 10 cm. The last performance metric incorporated in the model is the construction and repair costs of the measures. These costs will depend on the selected measures and whether failure occurs in the given scenario. Costs are calculated by multiplying the unit costs with the length and height of the chosen measure.



(a) Example of a depth-damage curve for a 2-story residential structure and its contents (USACE - Galveston, 2003)



(b) Example of a frequency-damage curve, a type of risk curve. The curve shows the reduction of the probability of exceedance of damage. (van Berchum, 2022)

Figure 3.7: Examples of depth-damage and frequency-damage curves

3.3.5. Risk profile assembly

Just a single flood scenario is insufficient to evaluate the performance of a flood risk reduction strategy. A risk profile, constructed from the results of multiple scenarios, gives a better indication of overall performance. It can be made by evaluating the same flood risk reduction strategy for different hydraulic boundary conditions and adding weights to the results proportional to the chance of the boundary conditions occurring. For example, when the boundary conditions for a 5-, 10-, 50-, 100- and 500-year event are known, the model is evaluated five times. The risk profile then visualises the damages in relation to the probability. Figure 3.7b shows the principle of a risk profile with and without implementing a flood risk reduction strategy. The curves show the probability of exceedance of damage, whereas the shaded area under the solid line is the total risk expressed in dollars/year. The dashed line represents a reference situation, and the arrows indicate the reduction in total risk due to a successful flood risk reduction strategy.

Large storms, such as hurricanes, frequently result in both storm surges and substantial rainfall. As a result of this correlation, it is essential to acknowledge that storm surge occurrences and extreme rainfall events are not independent stochastic variables. In low-lying coastal areas, the chance of flooding for a combination of the two events is much larger than from either in isolation (Wahl et al., 2015). Considering both hazards as independent would lead to underestimating the total risk. Therefore, an adjustable correlation coefficient is implemented in the model to address this. However, to keep the scope of research manageable, this correlation coefficient is neglected, and the hazards are all considered independent.

3.3.6. Flood simulation model outputs

A range of outputs can be obtained from the FLORES model. Most importantly, the total damage in the area of interest and exposed population as a result of the input storm and applied measures. To gain more insight into the specific areas at risk, these numbers can also be shown per basin, as well as the maximum water surface elevation during the storm in each basin. With these numbers, the effect of measures can be better understood. Furthermore, the total values of the hydrological balances are summed up to check if the calculations have been performed without any significant errors. There should be no large discrepancies in the total volume of water that has entered, left, and is stored in the system. When water disappears, there is likely an error in the model or one of the model's inputs.

Lastly, the model also calculates the total cost of the chosen measure or combination of measures. To determine the damage reduction, the model is run for the same hydraulic boundary conditions, both with and without the measure(s). By comparing the reduction in damages to the total costs, the benefit-cost ratio of the measure(s) can be found for those specific circumstances. This analysis enables us to determine whether the benefits outweigh the costs and thus quantify the effectiveness of any combination of measures.

3.4. Exploratory modelling

The FLORES model can perform exploratory modelling by incorporating the EMA workbench, a Python package developed by Kwakkel (2015). The package provides many options for setting up, designing and performing a series of computational experiments on one or more models simultaneously. The package also offers many options for analysis and visualisation of the computed results. These options include: Patient Rule Induction Method (PRIM), Feature Scoring (FS), Regional Sensitivity Analysis (RSA) and pair wise plots. The results of these analysis methods are needed to construct the adaptive pathways.

3.4.1. Running experiments

In order to observe the effects of measures and to identify which measures are most effective, it is first necessary to observe the outcome of the model for all combinations of scenarios and strategies. The EMA Workbench defines a scenario as a combination of uncertainties. An uncertainty, is a parameter which can be implemented as a uniform distribution between a given minimum and maximum value. Examples of uncertainties are rising sea levels, future development, and the effects of climate change. A strategy is a combination of measures.

The model in question is evaluated for n scenarios times m strategies. For a large number of possible scenarios and strategies, the number of required evaluations can increase exponentially. Therefore, it is advisable to limit one of the two. Either consider a limited number of strategies or a limited number of scenarios. The total number of model evaluations can increase quickly as it increases exponentially with the number of uncertainties, strategies and scenarios.

Effect of uncertainties on possible scenarios
Say we have only one strategy to investigate and one uncertain parameter ranging from 0 to 1, with steps of 0,1. In this case, we have to evaluate the model for 10 scenarios. If we add another uncertainty with the same characteristics, the total number of scenarios rises to 10 times 10 = 100 scenarios. For three uncertainties, the total number of scenarios is 1000. Thus, doubling the number of uncertainties leads to a tenfold increase in the number of calculations. The following formula can be used to express this:

$$total\ scenarios \propto a^n$$

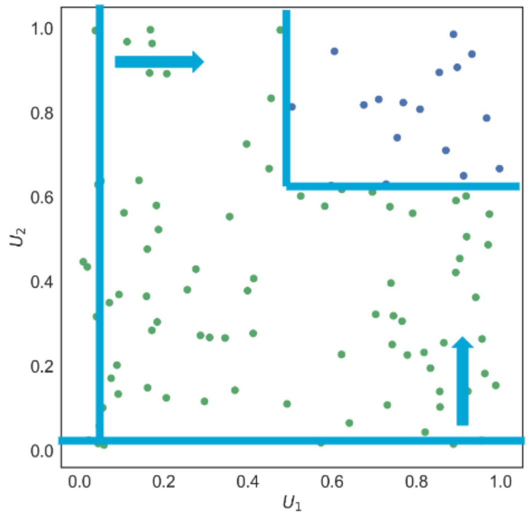
Where n is the number of uncertain parameters considered.

An alternative to speed up the computation time required to explore the FLORES model for all the possible combinations of scenarios and measures is to enable multi-core computing. A modern computer's Central Processing Unit (CPU) comprises multiple cores that run side by side. While each core can only perform tasks sequentially, multiple cores can be tasked to run calculations of the same model simultaneously. In this way, the computation time can be significantly reduced without needing special hardware as long as the computer has multiple cores available. This is already built into the EMA workbench and can easily be used.

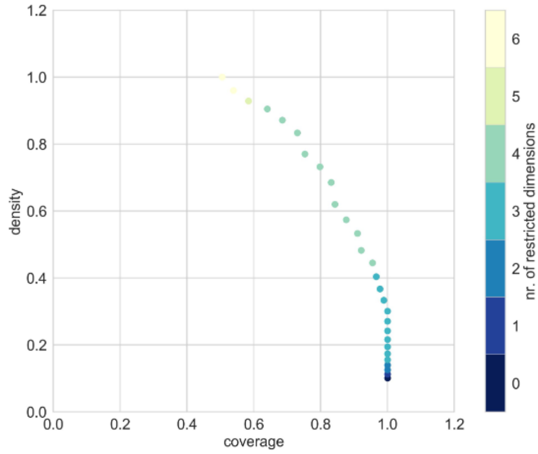
After running the model for all the possible combinations of scenarios and measures, the resulting outcomes are saved in a database with the specific inputs used for that model run. Each line of the database represents one run of the model and lists the used input parameters, applied strategy, scenario, and model outcome(s). By saving all this information in a database, the user can use many analysis methods easily without re-evaluating the model. The realisations of the model only have to be generated once unless inputs of the model or the model itself change, of course.

3.4.2. Analysis methods

The second step in the process is to identify the most effective measures. Several tools are available to help the user make sense of the large amount of data and identify patterns. This section briefly explains the tools relevant to this thesis.



(a) The space is peeled step by step to obtain the subspace. Blue dots represent desired outcomes, and green dots represent undesired outcomes.



(b) Effect of peeling on the density and coverage. Each dot represents a peeling step, starting at the bottom right.

Figure 3.8: Subspace partitioning using PRIM (Kwakkel, 2023)

Feature Scoring (FS)
The feature scoring tool is one of the most essential tools for better understanding the system's behaviour. A feature scoring analysis determines the influence all the inputs (uncertainties and strategies) have on the model's outcome. If a large influence exists between a measure and the outcome, this measure should be considered first. Feature scoring will be performed for the current conditions and each scenario. This analysis will help guide the formation of the pathways by determining which measures have the largest influence on achieving an ineffective design.

Patient Rule Induction Method (PRIM)
Subspace partitioning can help to identify the effect of uncertainties on the model outcomes. This method works by finding rules in uncertainties which lead to specific outcomes. For models with only two uncertainties and a single outcome, this can still be done visually on paper. When mapping out the results on two axes, all desired results lie between two values for each of the uncertainties. However, if more uncertainties and/or more outcomes have to be considered, this becomes impossible to do by hand. Therefore, rule induction algorithms have been developed to help identify rules in uncertainties that lead to the desired outcomes. Four algorithms are included in the toolbox: CART, PRIM, Dimensional Stacking and Logistic Regression. PRIM is used as the visualisation method as it produces nice trade-off curves and can show the effectiveness regions of measures.

The PRIM algorithm works by limiting the total output space step-wise. The density of desired outcomes left in the subspace is measured for each step. Density refers to the number of desired outcomes divided by the total number of outcomes in the subspace. The algorithm tries to increase the density for each step until the density can not increase further; this process is called peeling. During the peeling process, the coverage and the fraction of cases of interest within the box decrease. At the same time, the number of restricted dimensions increases. An example of this process is given in Figure 3.8b. The PRIM algorithm will identify trade-offs and determine which measures can achieve the desired risk reduction.

Effectiveness Regions
Van den Broek (2019) used the concept of effectiveness regions to show the effectiveness of individual measures under differing external factors. These indicate whether a measure is cost-effective for each measure for the specified range of uncertainty. It is possible for a measure to not be cost-effective for all possible values of the uncertain parameter or only become cost-effective after a set amount of increase

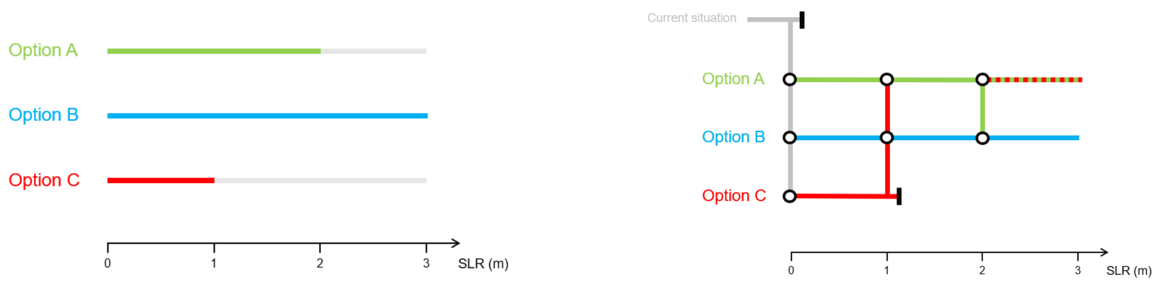
in development. For example, when the value in a flood-sensitive area increases due to investments in new homes or industries, providing better flood protection measures might become cost-effective. Effectiveness regions can be constructed for one changing uncertainty or multiple. This creates a subspace of scenarios where measures are cost-effective for each measure.

When a measure is not cost-effective, it will not be considered when creating the adaptive pathway for that range of uncertainty. Multiple measures might be cost-effective under the same scenario; in this case, both measures are possible, or perhaps a combination of measures. The final decision is up to decision-makers based on the other properties of the measures and societal preferences. Total cost, benefit-cost ratio, public support, environmental effects, future concerns, construction time, affected population and many more characteristics of the measures at play in the decision-making process.

3.5. Interpretation of results

The last step of this thesis is to construct the Dynamic Adaptive Policy Pathways, from now on pathways, themselves. Pathways are constructed for each uncertainty separately and for each combination of uncertainties. First, PRIM analysis determines the effectiveness regions of the measures. Figure 3.9a gives an example of effectiveness regions for three measures under sea level rise. When a measure no longer achieves its goal, it is deemed ineffective, and that path ends. This is also called an adaptation tipping point, and a different measure must be implemented to achieve the goal. In some cases, a combination of two measures can also be effective, for example, a combination of measures A and C for 2+ meters sea level rise in Figure 3.9b. Thus, pathways consist of measures or combinations of measures and change over time as some measures might become ineffective or only effective as time goes on and boundary conditions change.

The pathways can be evaluated based on scoring criteria like benefit-cost ratio, affected population and environmental impact. The pathway with the highest score is the optimal pathway. The optimal paths for each (combination of) uncertainties can be combined in a three-dimensional chart, where the axes are the uncertainties. In this way, the optimal path for all plausible scenarios can be visualised in one graph, and it is easy to see which future options are optimal under changing conditions.



(a) Effectiveness regions of three options under sea level rise. **(b)** Pathways considering three options under sea level rise.

Figure 3.9: Example of how pathways are constructed.

Other useful information can also be extracted by analysing the pathways. Important trade-offs between measures and pathways can be identified. Lock-ins, where changing measures becomes unfavourable and only continuation of the current (set of) measure(s) is possible (measure B in Figure 3.9b), can be recognised ahead of time and avoided if desired. For example, consider Figure 3.9b, when switching from measure C to B, the investment in C was potentially useless. Furthermore, short-term measures can be suggested based on the optimal pathways, and a monitoring plan is enabled to track relevant indicators that indicate adaptation tipping points.

4 Case study: model setup for Galveston Bay

This chapter covers the setup of the FLORES model for Galveston Bay. Firstly, the local situation and proposed plans are discussed in Section 4.1. Secondly, the possible future scenarios used for the case study are elaborated in Section 4.2. Thirdly, an overview of the required pre-processing of the elevation, land value and population data is given in Section 4.3. Next, Section 4.4 gives an overview of the areas sensitive to flooding. Section 4.5 explains the measures which have been considered in the case study. Lastly, Section 4.6 shows the validation of the model.

Disclaimer: This thesis presents an academic research endeavour and does not serve as an exhaustive design report. It employs a simplified model, cautioning that the inputs utilised herein may not be directly comparable to those in other studies. The costs depicted are notably smaller than those used in related design and feasibility reports. Furthermore, the calculated risk reduction may differ due to varying methodologies, and the model's level of detail is limited. Readers are advised to interpret findings within the context of academic inquiry rather than practical application.

4.1. Situation

Several plans for the protection of the Galveston Bay area have been proposed and elaborated in varying amounts of detail. The goal of this section is to present the most important proposed plans and to discuss some of the missing details and criticisms of the plans.

4.1.1. USACE proposed plan

The US Army Corps of Engineers (USACE) has proposed a coastal protection plan in its first feasibility report in 2020 (USACE, 2020), which can be seen in Figure 4.1. The plan is based on the Coastal Spine concept proposed by Merrell et al. (2011). The main element of the plan is the construction of a primary defensive line right along the coast of Bolivar Peninsula and Galveston Island, the Coastal Spine. This defence consists of a beach and dune system on the Bolivar Peninsula and West Galveston Island, improvements to the Galveston Seawall and the Bolivar Roads Gate System. The last system consists of a storm surge barrier for ship traffic, along with a series of environmental gates to maintain the exchange of water between the bay and the Gulf of Mexico.

The main philosophy of the USACE plan is to shorten the coastline by placing the primary flood defences right along the coast as the Dutch have done with the Delta Works along the coast of Zeeland. By applying this strategy, the total required length of primary flood protection can be reduced significantly. However, this philosophy can not be applied directly to the Galveston Bay area. Due to the large area of the bay, the depth of water in the bay and extremely high wind speeds caused by hurricanes, the water level set up on the west coast of the bay can become significant during storms. The set-up can become large enough to cause flooding on the west coast of the bay.

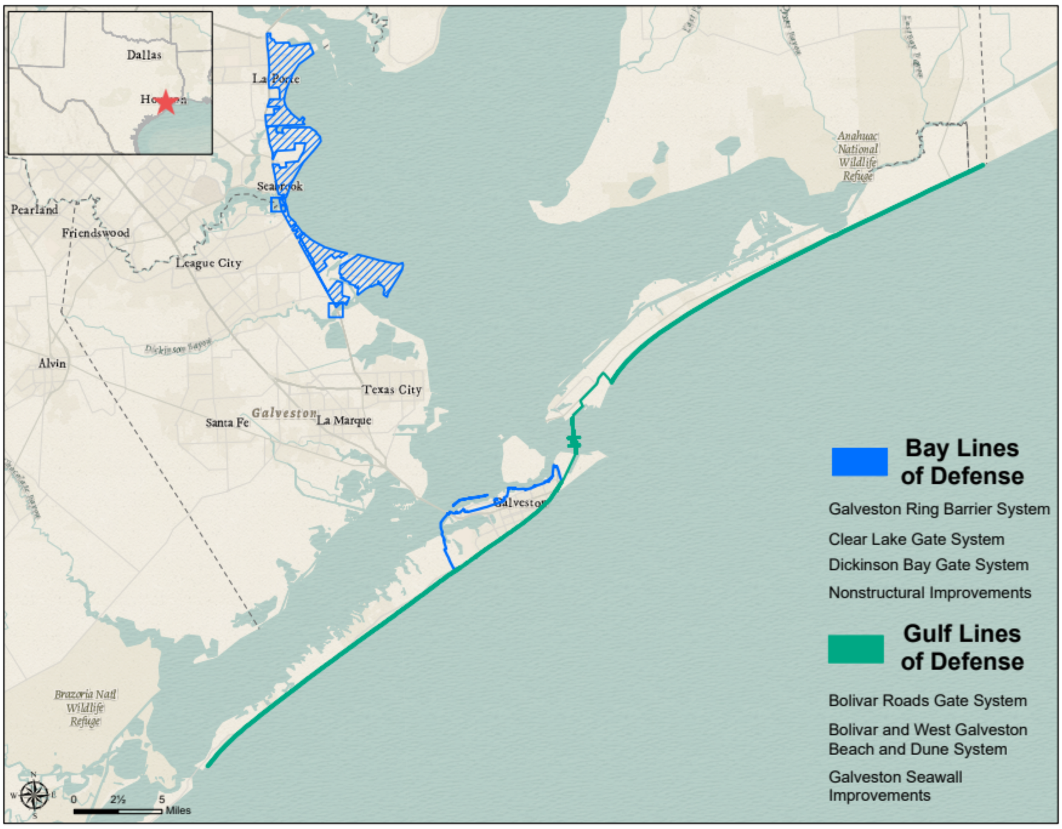


Figure 4.1: Overview of the proposed USACE plan (USACE, 2021b)

Consequently, additional flood protection measures are needed behind the land barrier in the bay, especially on the developed and populated west side. Firstly, the 'back side' of the city of Galveston, which faces the bay, must be protected against flooding. The USACE proposes a ring barrier around the city. How a ring barrier will be implemented in a busy harbour district is left open. Secondly, the Clear Creek and Dickinson Bayou areas are at a significant risk of flooding. The USACE proposes using Highway I146 as a dike with a storm surge barrier in each estuary for navigational purposes. Once again the exact details of these barriers are left unclear. Thirdly, there is also a risk of flooding in the towns directly along the bay: La Porte, Bacliff and San Leon. The USACE plan proposes nonstructural improvements in these areas.

4.1.2. Galveston Bay Park Plan

The Galveston Bay Park Plan (GBPP) was proposed by the SSPEED centre in 2019 (Bedient, 2022) and can be seen in Figure 4.2. The mid-bay barrier is the main feature of this plan; it involves the construction of a line of artificial islands that goes through the bay alongside the Houston Ship Channel. At the location where the channel crosses the barrier, a large barge gate has been envisioned for ship traffic to the Port of Houston. Also, several smaller gates in various locations are included in the plan to allow for navigation of smaller (recreational) vessels. The plan is focused on protecting the densely populated west coast of the bay and the petroleum industry of Houston. Consequently, the plan enjoys support from the Port of Houston, City of Houston and Harris County.

However, a primary line of defence is also required because the mid-bay barrier does not provide sufficient protection to communities on the barrier islands of Bolivar Peninsula and Galveston Island or the east side of the bay. Therefore, the GBPP also envisions a primary protection in the form of a Coastal Spine. This design will be similar to the first line of defence of the USACE plan but leaves out the storm surge barrier near Galveston.

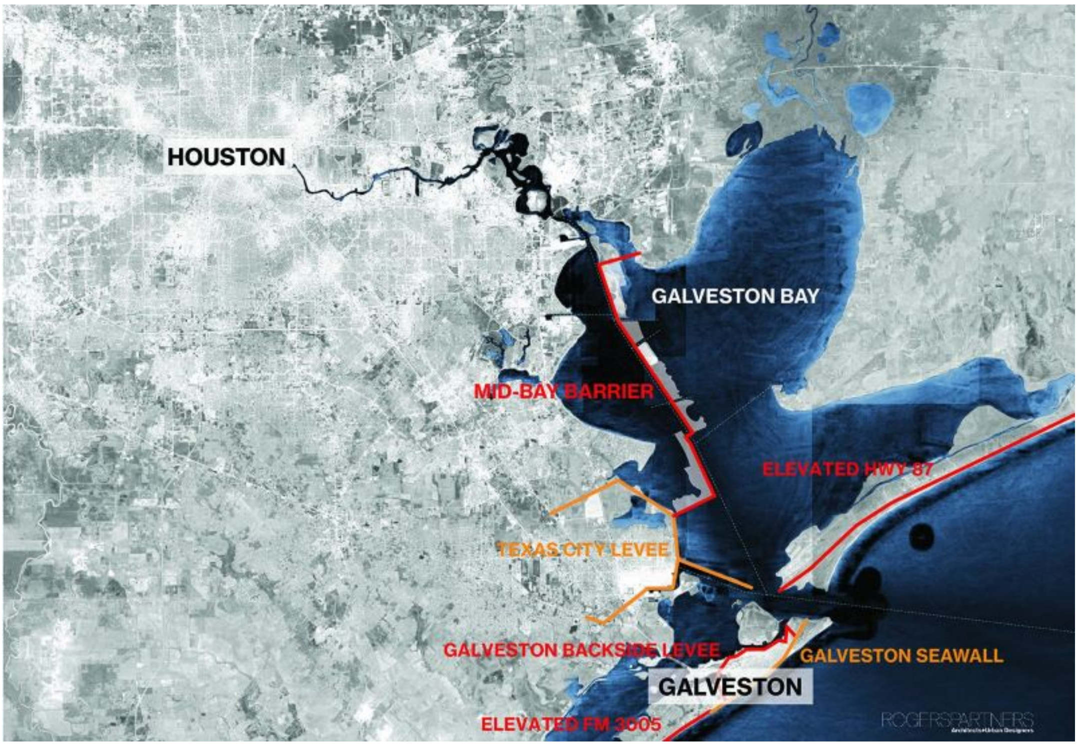


Figure 4.2: Overview of the Galveston Bay Park Plan (Rogers Partners, 2023)

The main difference between the GBPP and the USACE plan is the approach to the in-bay measures. Whereas the USACE proposes a more inland line of defence, the SSPEED centre moves the barrier out to the bay. The SSPEED centre approach offers multiple advantages. Firstly, the barrier can be constructed completely in the bay, and no properties have to be bought out to construct the levees. Secondly, the Port of Houston and Houston Ship Channel are better protected by the mid-bay barrier. Thirdly, the barrier is constructed of dredge spoils from the channel, reducing costs greatly. Parts of the mid-bay barrier already exist as dredge spoil islands, and maintenance of the islands is virtually free as the channel will be dredged anyway.

4.1.3. Discussion of current plans

While the USACE plan largely builds upon the concept of the coastal spine, the proposed dike along the Bolivar Peninsula is replaced with a double dune system. According to Ebersole (2021) the double dune will lead to a significantly lower level of protection. This replacement leads to high residual damages compared to the investment costs and is an area of improvement. Furthermore, as proposed in the current plan, there is a significant risk of flanking the Clear Creek and Dickinson Bay surge barriers. In contrast, the GBPP does provide comprehensive protection to these areas, as it is connected to the Texas City dike in the south and links up to high land in the north. But, the mid-bay barrier will have a greater impact on the environment by partitioning the bay. A critical comparison between the measures taken inside the bay and their effectiveness under varying conditions can be valuable information to local policymakers. An overview of the exact measures considered in this thesis is provided in Section 4.5.

4.2. Future scenarios

Predicting future changes for the next 5 or 10 years is relatively straightforward. Often, it is possible to extrapolate from current developments and forecast the effects of policies implemented by politicians. However, predicting these changes for the next 50 years or more becomes virtually impossible, considering the ever-growing rate of change in the world. For example, events such as the Russian invasion of Ukraine, which caused gas prices to skyrocket in Europe, have decreased the European dependency on (Russian) gas faster than anyone could have predicted. This illustrates that great change is possible in a short amount of time if there is political will. Therefore, it is more beneficial to think of the future in scenarios and think about all the possibilities rather than trying to find the most probable future.

This section creates scenarios based on narratives describing developments of the uncertainties that have been considered for this research. The major uncertainties pertain to the effects of climate change and developments in the Galveston Bay area. Climate change affects the hazard side of the flood risk: rainfall, sea level rise and more extreme storms. Development affects the consequences of the flood risk: a larger exposed population and increased asset value. Although the scenarios cover plausible futures, they should be grounded in reality. Therefore, an analysis is made to determine what is inside the realm of possibility.

4.2.1. Climate change

Predicting the exact effects of climate change is virtually impossible and a field of research on its own. Therefore, it is best to think about climate change in the form of possible scenarios. This thesis follows the Representative Concentration Pathways (RCPs) put forth by the IPCC Fifth Assessment Report (2014). The pathways describe climate change scenarios based on the amount of greenhouse gasses emitted in the future, see Figure 4.3. The RCPs are labelled by their respective value of radiative forcing in the year 2100. This thesis considers the scenarios with 1.9, 4.5 and 8.5 W/m^2. The scenarios can be described as follows: RCP 1.9 limits global warming to 1.5°C, which is the aspirational goal of the Paris Agreement. RCP 4.5 represents an intermediate scenario, and in RCP 8.5, greenhouse gas emissions continue to rise throughout the 21st century. This thesis follows the RCPs because the results of climate change research are often linked to these scenarios.

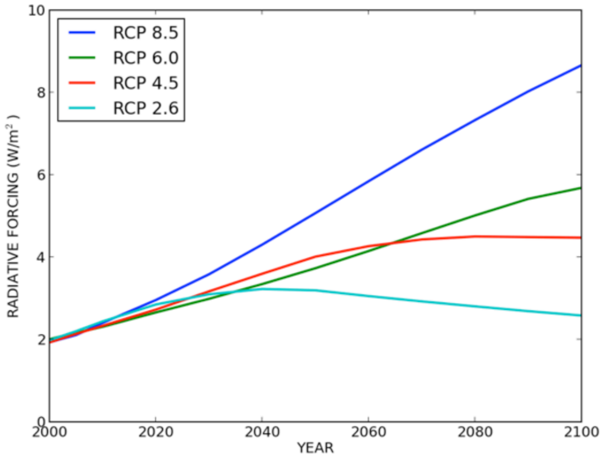


Figure 4.3: Representative Concentration Pathways (Emanuel & Janetos, 2013)

Extreme weather

One aspect of climate change revolves around the rise in more frequent occurrences of extreme weather events. Over the past few decades, floods and high tides, among other extreme events, have been happening more frequently and with greater intensity (USACE, 2021b). Predictive models for future hurricanes indicate that, due to climate change, there will be a slight increase in hurricane wind intensity (Knutson et al., 2020b). While the frequency of hurricanes may not change significantly or even slightly decrease, a larger proportion of the storms are projected to reach more intense levels, categorised as Category 4 or 5 (Colbert, 2022). Additionally, Knutson (2020a) highlights that models also demonstrate an increase in the precipitation rate associated with hurricanes.
Meanwhile, current models used for flooding seem to be too optimistic, as Harris County has been hit by eight rare storms since 1989. Five of those storms were qualified as 1 in 100-year storms, and 3 of those were even rarer (Satija et al., 2016). While there is a chance this is just a coincidence, the chance of this happening is so slim that it is much more likely the models used to qualify 1 in 100-year floods are inaccurate, outdated or both.

Relative sea level rise

Another aspect of climate change is relative sea level rise, which is the combination of sea level rise and land subsidence. Between 1901 and 2018, the average global sea level rose by roughly 1 to 2 mm/yr (IPCC, 2022). However, in the last decade (2013 - 2022), sea level rise has accelerated significantly to 4.62 mm/yr (World Meteorological Organization, 2023). This acceleration makes accurately predicting the rise of sea level in 50 years almost impossible. Especially because the effects and processes of sea level rise are not fully understood and because it is also dependent on the actions of humans. More aggressive or lax climate policies of the largest polluters can have a significant impact on the rate of sea level rise, although there is a considerable delay between the action and effect. Meanwhile, land subsidence caused by the extraction of hydrocarbons and the over-utilisation of aquifers reinforces the effects of sea level rise. Studies (Miller & Shirzaei, 2021) have shown that land subsidence rates during a study period of 2007-2009 have reached 13.3 $\pm$ 1.5 mm/year in the northwest of Houston. Locations such as Dickinson Bay, Texas City, and Galveston all experience subsidence, although less aggressive.

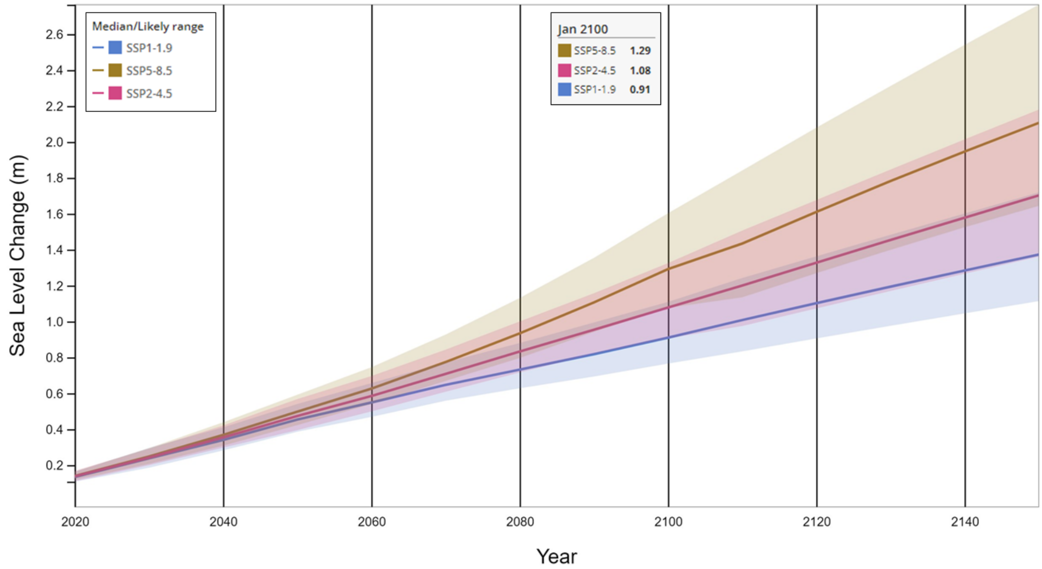


Figure 4.4: Projected relative sea level rise under different SSP scenarios at Galveston Pleasure Pier, TX (NASA, 2023)

Figure 4.4 shows the relative sea level change projection at Galveston for the very low (SSP1-1.9), intermediate (SSP2-4.5) and very high (SSP5-8.5) emission scenarios. The numbers after the - represent the RCP scenario.

4.2.2. Development

The Houston area has seen steady growth in terms of population, and, as of 2022, Harris County is the third-most-populous county in the United States (United States Census Bureau, 2022). If the population continues to expand, more people might be pushed to live in flood-prone areas due to the relatively low costs of property in these locations. This development increases the risk to human lives and property when no measures are taken. Meanwhile, the petroleum and chemical industry located in the Port of Houston also continues to develop and expand. The petroleum and chemical industry is mostly located along the coast of Galveston Bay or along other water bodies because shipping is the most efficient way to transport the products made by these industries. The downside of this placement of industry is the high risk of flooding when a hurricane occurs.

This thesis considers two scenarios: one based on growth and a second scenario based on decline. Development Pathway 1 (DP1) represents the continued growth of the Houston area. Historically the Houston metro area has seen a growth of 2% year over year, which has slowed down in recent years to about 1.5% year over year (www.macrotrends.net, 2023). Hoque (2014) forecasts a total population growth of 69% between 2010 and 2050, assuming net migration equal to one-half of 2000-2010. This is the middle scenario used in the study. Development Pathway 2 (DP2) represents the decline of the area. Global developments towards green energy alternatives can lead to a decline in the local industry and population, similar to what has happened in Detroit, for example. In this case, a decline of 30% is used.

4.2.3. Implementation of scenarios in the model

This section details the implementation of the aforementioned scenarios in the FLORES model. The RCP 0 and DP 0 scenarios are added; these do not apply any changes to the model and are the baseline of reference. Table 4.1 shows the implementation of the climate change scenarios. Sophisticated models for the projection of relative sea level rise around the world based on RCP scenarios have been developed. For this report, the sea level projection tool of NASA (2023) based on the aforementioned RCP scenarios has been used. Wind velocity and rainfall intensity are implemented as multiplication factors and based on Knutson (2020a). Knutson analysed the results of many studies on the change in tropical cyclones for a global 2°C increase. Such an increase is expected to occur around 2080 in the RCP 4.5 scenario. For RCP 1.9 and 8.5, the 25% and 75% values were used.

Table 4.1: Representative Concentration Pathways and their effects, wind velocity and rainfall intensity are implemented as multiplication factors (>1 represents an increase)

Name	Pathway	RSLR (m) in 2080[1]	Wind velocity[2] (-)	Rainfall intensity[2] (-)
RCP 0	Current	0	1	1
RCP 1.9	Paris agreement	0.57	1.015	1.09
RCP 4.5	Intermediate	0.83	1.03	1.15
RCP 8.5	Worst case	1.31	1.05	1.21

The implementation of the development scenarios can be found in Table 4.2. The industry at risk value is a multiplication factor applied to all industrial and commercial properties, thus increasing the value of these properties. Similarly, the population at risk value is also a multiplication factor applied to residences, thus increasing the population of these properties. Forecasts provided by Hoque (2014) are used for the DP 1 scenario.

Table 4.2: Development pathways and their corresponding multiplication factors (>1 represents an increase)

Name	Pathway	Economic value (-)	Population (-)
DP 0	Current	1	1
DP 1	Growth	1.7	1.7
DP 2	Decline	0.7	0.7

4.3. Input data for the FLORES model

Before the FLORES model can be applied, the input data required for the model must be collected or otherwise created. This section will show what data was gathered, the required preprocessing steps, and how they were used.

4.3.1. General overview

Table 4.3 shows the data used for the hydraulic boundary conditions of the model. Water surface elevation (WSE), wind velocity and wave height could all be gathered from the same storm surge model provided by Bedient (2023). Rainfall data was obtained from the National Oceanic and Atmospheric Administration (NOAA) for the Galveston weather station.

Table 4.3: Hydraulic boundary conditions

Dataset	Description	Source
Storm data	Maximum Water Surface Elevation (WSE), wind velocity and wave height	SSPEED (2023)
Rainfall	24-hr precipitation frequency estimates	NOAA (2018)

[1]Adapted from (NASA, 2023)
[2]Adapted from (Knutson et al., 2020b)

Further input data was mainly GIS-based, such as the parcel-level land value data, block-level population data and the digital elevation model. Table 4.4 provides a list of the sources used. Input data for the measures was taken from the USACE Feasibility Report (USACE, 2021b) and Galveston Bay Park Plan (Bedient, 2022).

Table 4.4: Input data for FLORES

Dataset	Description	Source
Digital Elevation Model (DEM)	Raster dataset with 0.5 meter horizontal resolution, 10 cm vertical accuracy.	TNRIS StratMap (2018)
Land value	Property and land value on a parcel basis.	TNRIS (2019)
Population	Population numbers on a block level.	U.S. Census Bureau (2022)
Damage curves	Depth-damage curves for several categories of buildings.	(USACE, 2021a)

4.3.2. Storm surge and rainfall data

Proxy storms have been defined for the 10-, 100- and 500-year average recurrence intervals of the water surface elevation based on water surface statistics by Ebersole et al. (2018). In this study, three individual storms from the 223-storm FEMA (2011) dataset were selected as proxy storms. These are storm 535 as a 10-year proxy, storm 033 as a 100-year proxy and storm 036 as a 500-year proxy. All storms followed Track 4 of the TXN Fan set, which makes landfall near San Luis Pass.

Different groups performed extensive storm surge modelling for Galveston Bay. A single source that has modelled both these situations has been chosen to validate the maximum water surface elevation for the Coastal Spine solution and the GBPP solution. The SSPEED centre calculated the flood levels for the current situation, Coastal Spine and GBPP design if storm 036 were to occur (Bedient, 2023). Storm 036 is equivalent to a category 4 hurricane, with wind speeds up to 130 miles per hour. Figure 4.5 shows the inundation in the Galveston Bay area when protected by the Coastal Spine and GBPP and subjected to storm 036. The WSE of 24.5 feet at the Galveston Pleasure Pier will be used as a hydraulic boundary condition for the FLORES model. The various measurement points inside the bay and in the HSC will be used for verification of the model.

About rainfall data, the NOAA's National Weather Service publishes the Precipitation-Frequency Atlas of the United States (Perica et al., 2018). This Atlas provides point precipitation frequency (PF) estimates for many locations in the US. PF estimates are based on frequency analysis of partial duration series. For this thesis, the estimates for the Galveston weather station are used, which can be found in Table 4.5. Galveston was chosen as it is the same location from which the WSE data was taken, and the rainfall for the entire west coast of the bay is between 17 and 18 millimetres/hour for the 100-year 24-hour precipitation. Appendix B shows the rainfall isopluvials for the entire Texas state. As explained in Section 3.3.5 rainfall and storm surge events are considered independent to limit the scope of this thesis.

Table 4.5: PDS-based precipitation frequency estimates (in millimetres/hour) (Perica et al., 2018)

	Average recurrence interval (yrs.)		
Duration	10	100	500
24-hr	9	18	28
48-hr	5	11	16
72-hr	4	8	11

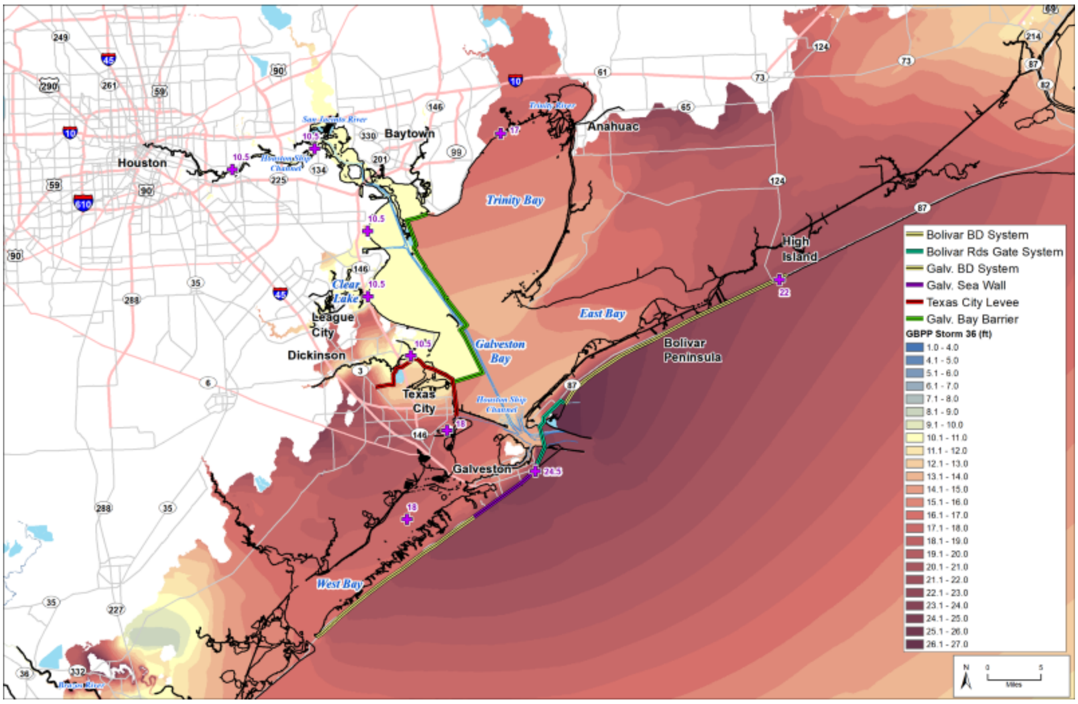


Figure 4.5: Maximum water surface elevation in the Galveston Bay area hit by storm 036 with the Coastal Spine and Galveston Bay Park Plan implemented (Bedient, 2023)

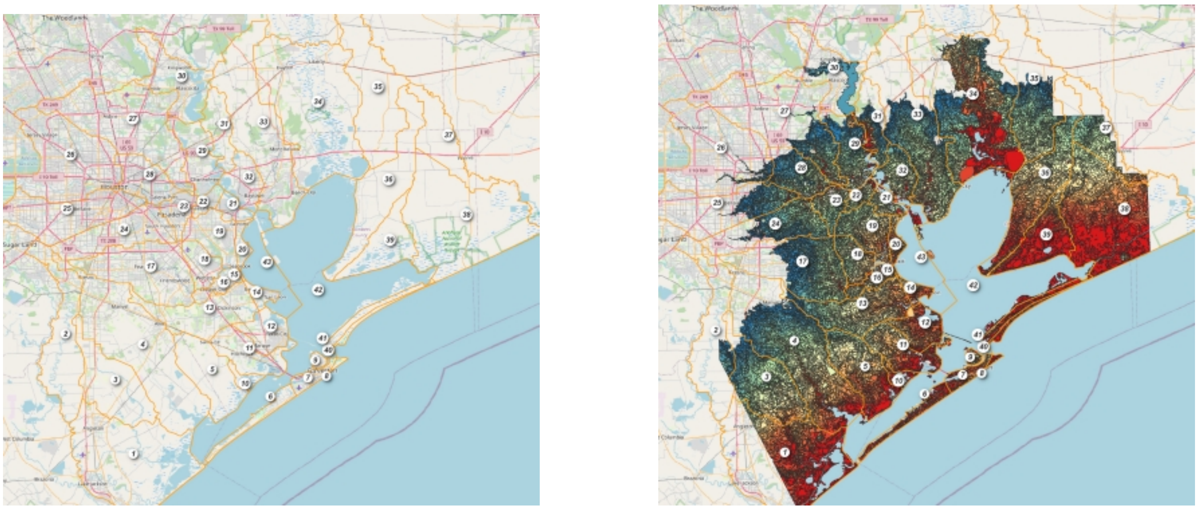
4.3.3. Preprocessing of elevation, land value and population data

The elevation, land value and population data come in various formats. Preprocessing is required to unify these formats, remove errors, create new data fields and merge the data into a single output suitable for the FLORES model. The preprocessing has been executed in QGIS, and a complete description of the process can be found in Appendix A. This section gives only a brief overview of the process.

First, the region is divided into 43 watersheds based on the Digital Elevation Model (DEM) (Strategic Mapping Program (StratMap), 2018) and the HUC10 basins (USGS). Each of these watersheds is then divided into contours of 0.25 meters high, based on the DEM. The DEM is based on LIDAR data and has a horizontal resolution of 0.5 meters but is simplified to 10 meters to decrease computation time. However, this simplification does keep the advantage of the high vertical accuracy of the LIDAR data. To limit computation time further, the highest contours are defined at 15 meters above sea level; this is assumed sufficiently high for no floods to occur. Figure 4.6 shows the result of the DEM preprocessing.

Next, the land value per development category is added to the contours. The land value dataset is intersected with the previously defined contours. This process transfers the properties of the land value data to the contours and sums up the value per category per contour. Damage curves for every type of land use are derived from the USACE (2021a). By combining the inundation depth of a contour with the value per land-use type per contour and the damage curves, the total damage per contour for a given inundation depth can be found. Structure type and value are supplied by TNRIS and based on the local county appraisal districts (Strategic Mapping Program (StratMap), 2019). Lastly, the population data provided per block is added in a similar fashion.

The value of refineries and chemical plants is a point of attention. Data from appraisal districts covers the value of homes very well, however data on the petrochemical industry is extremely limited. Recently, in 2022 Shell Oil Company sold its 50.005% percent stake in its Deer Park oil refinery for $596 million (Shell Global, 2022). This sale places the total value of the Deer Park refinery at $1.2 billion. The total area of the refinery is 2300 acres or 100 million square feet. Dividing these two gives a valuation of $12 per sq ft (for the entire property, not just buildings). This value is used for all refineries and chemical plants in the Galveston Bay area because of a lack of better data.



(a) Basins in the Galveston Bay area

(b) Watersheds divided into 0.25-meter contours

Figure 4.6: Result of DEM preprocessing

4.3.4. Depth-damage curves

The damage to a structure is related to the local flood level by depth-damage curves, which show the percentage of the total structure value damaged at various flooding depths. Figure 4.7 shows the depth-damage curve for a 1-2 story house, as defined by the USACE - Galveston district. This curve is also applied in this research to all properties, as a detailed stock of raised houses and the number of floors per house was unavailable. The depth-damage curve is utilised to calculate the cost of replacing a flooded property based on its original value. For instance, a building with a structural value of $100,000 submerged with 2 meters of water above the first finished floor will experience a damage of 41%, which translates to a replacement value of $41,000 based on the property's value.

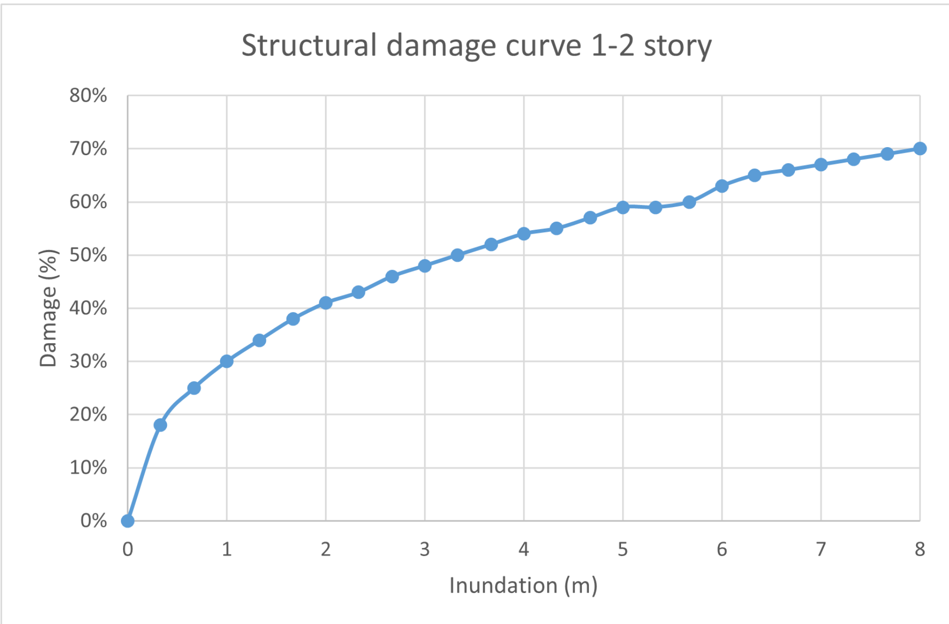


Figure 4.7: Depth-damage curve used in this thesis (USACE - Galveston, 2003)

4.4. Identification of risk

This section identifies the areas at risk and analyses the possible development of risk in the future. This thesis uses the following definition: risk equals the probability of flooding multiplied by the consequences of flooding.

4.4.1. Areas at risk

This subsection identifies the areas with the highest risk in the region. It is important to know where risk is concentrated when identifying possible measures to reduce this risk. Figure 4.8 shows the population density per contour; red indicates a high density, whereas blue indicates a low density. The main population centres of the region are clearly visible here: Galveston in basin 7, Texas City in basin 12, Dickinson and League City in basin 13 and the southerly suburbs of Houston in basins 17 and 24. When combining this information with the elevation data of the region, found in figure 4.6b, the highest level of risk is found in basins 7, 12, 13, 16 and 18. Measures to save lives in the event of flooding will likely focus on these areas, as the highest impact can be made here.

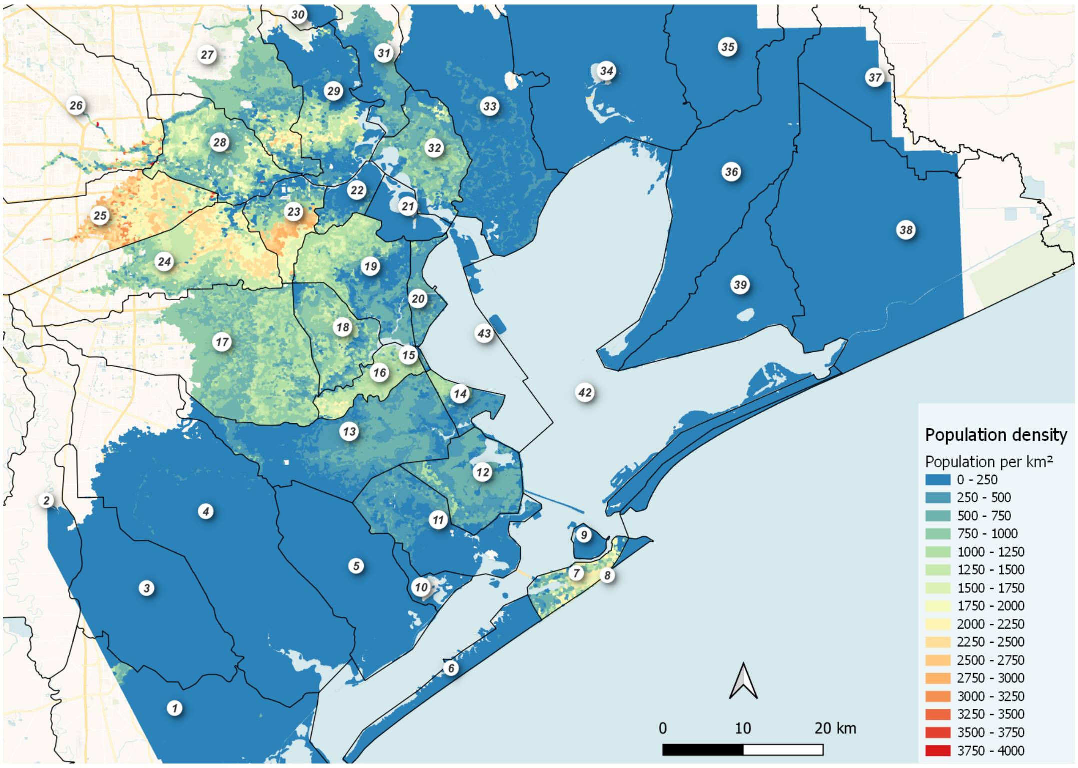


Figure 4.8: Population density Galveston Bay area, per contour

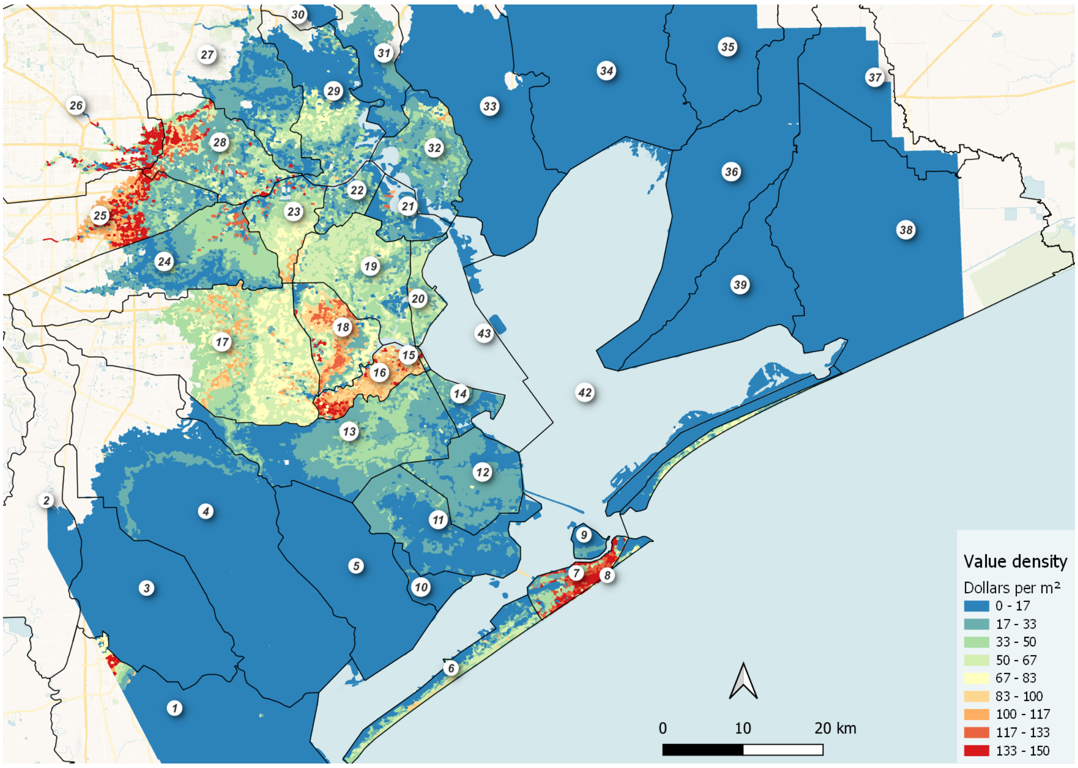


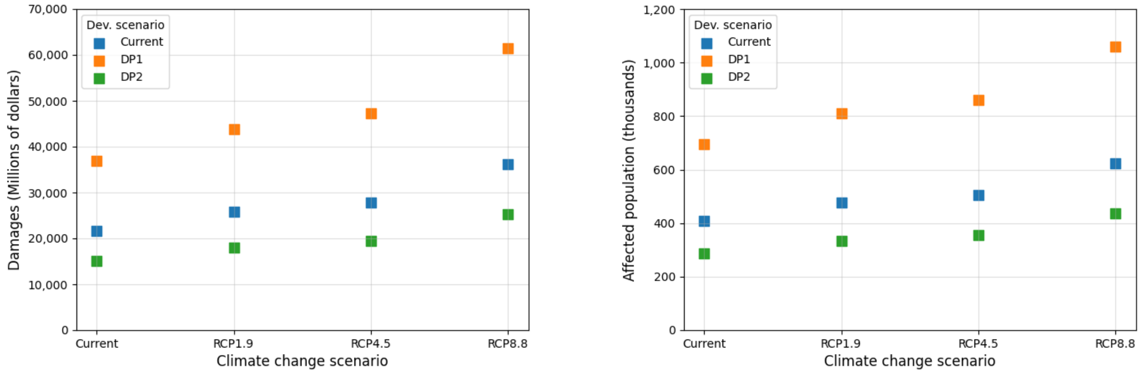
Figure 4.9: Land value density Galveston Bay area, per contour

Figure 4.9 shows the value of the development on land per square meter. A red colour represents a high value per square meter, and a blue colour represents a low value per square meter. A concentration of value in the greater Houston area in the top left of the map is clearly visible. Basins 16, 18, 19, and 20 especially show a high development value combined with a low elevation. Furthermore, a high value is found on Galveston Island. This high value corresponds with the city of Galveston in basin 7. However, along the coast of Bolivar Peninsula (basin 40) and the rest of Galveston Island (basin 6), the value is also fairly high, but this does not correspond to a high population density. This effect can perhaps be explained by the large number of second/vacation homes, which are not permanent residences but do represent a significant value.

Next to these areas, there is also some value at risk in the Dickinson Bayou area (basin 13 and 14) and Texas City (basin 12). While they do not represent as much value as the previous basins, there is still a significant risk here due to the low elevation of the area. Lastly, Figure 4.9 shows that the east coast of the bay signifies very little value, which was expected as it is mostly a nature reserve save for a few small settlements. The value of the east coast of the bay could be significantly higher if the natural value were considered. Natural value is neglected in this thesis to limit the scope of the research.

4.4.2. Development of risk in the future

Harris County was the second fastest growing county in the U.S. in 2022, adding more than 45 thousand people to the population (Ramos, 2023). The growth in population and changing climate conditions lead to an increase in the risk of flooding. Both the probability of flooding increases due to the effects of the rising sea level, reduced water retention of developed land and heavier rainfall, as well as the consequences of flooding due to the increase in population and investment in the region. Figure 4.10 shows the current risk of flooding as well as the increase in risk when the uncertainties increase for the Hurricane Ike storm event. In the base case, the total damages are $21,660 million, which can almost triple to $61,503 million under development pathway 2 combined with the RCP8.5 scenario. Similarly, the affected population more than doubles when comparing the base case to the worst case scenario, 409 thousand vs 1,060 thousand people affected. Clearly, different scenarios can have a significant impact on the total risk.



(a) Development of damages

(b) Development of the affected population

Figure 4.10: Effect of the scenarios on the damages and population affected under Hurricane Ike conditions.

4.5. Measures considered in the case study

Several measures to reduce or mitigate the flood risk are adapted from the proposed plans discussed in Section 4.1. In this section, the measures considered in this thesis are detailed.

4.5.1. Description of the measures

Land barrier

The land barrier is one of the main measures from both the USACE plan and the Galveston Bay Park Plan. It runs along the coast all along Galveston Island and Bolivar Peninsula. The red line in Figure 4.11 shows the location of this measure. The land barrier is implemented as an initial line of defence in the FLORES tool. The land barrier consists of a dual-dune system comprised of a 14-foot landward dune and a 12-foot seaward dune (4.3 and 3.7 meters, respectively) (USACE, 2021b). However, because this plan is not without criticisms, a suggested higher elevation of 17 feet or 5.2 meters is also modelled (Ebersole et al., 2021). For every time step of the simulation, the amount of overtopping of barriers is calculated. Failure of the land barrier is also considered.

Storm surge barrier

The storm surge barrier is the second measure from the USACE plan required to complete the Coastal Spine concept, along with the land barrier. It is situated at the Bolivar Roads inlet to Galveston Bay, where it connects to the land barrier on either side. The yellow line in Figure 4.11 shows the location of the storm surge barrier. The barrier is also part of the first line of defence in FLORES. Failure of the barrier is considered.

Midbay Barrier

The Midbay Barrier is the main feature of the Galveston Bay Park Plan. It follows the Houston Ship Channel (HSC) through Galveston Bay until it makes a sharp turn and connects with the Texas City levee. The proposed location of the midway barrier is represented by the green line in Figure 4.11. Dredge spoils from the HSC will provide the material for the construction of the levee, which will lead to significantly lower construction costs when compared to using virgin materials. Some parts of the levee are already constructed as dredge spoil islands. The plan will mitigate the residual risk in the bay by preventing large wind set-up during hurricanes from reaching the west coast of the bay. The main advantage of this measure is the complete protection of the entire west coast of the bay.

The Midbay Barrier is implemented in the form of a secondary line of defence in the FLORES tool. This line consists of a water barrier separating basins 42 and 43, with a large storm surge gate. Again, the amount of overtopping is calculated for every step of the calculation. Failure of the barrier can also be simulated. The Midbay Barrier is designed to become 25 feet or 7.62 meters high and will take approximately 5 years to complete (Bedient, 2022).

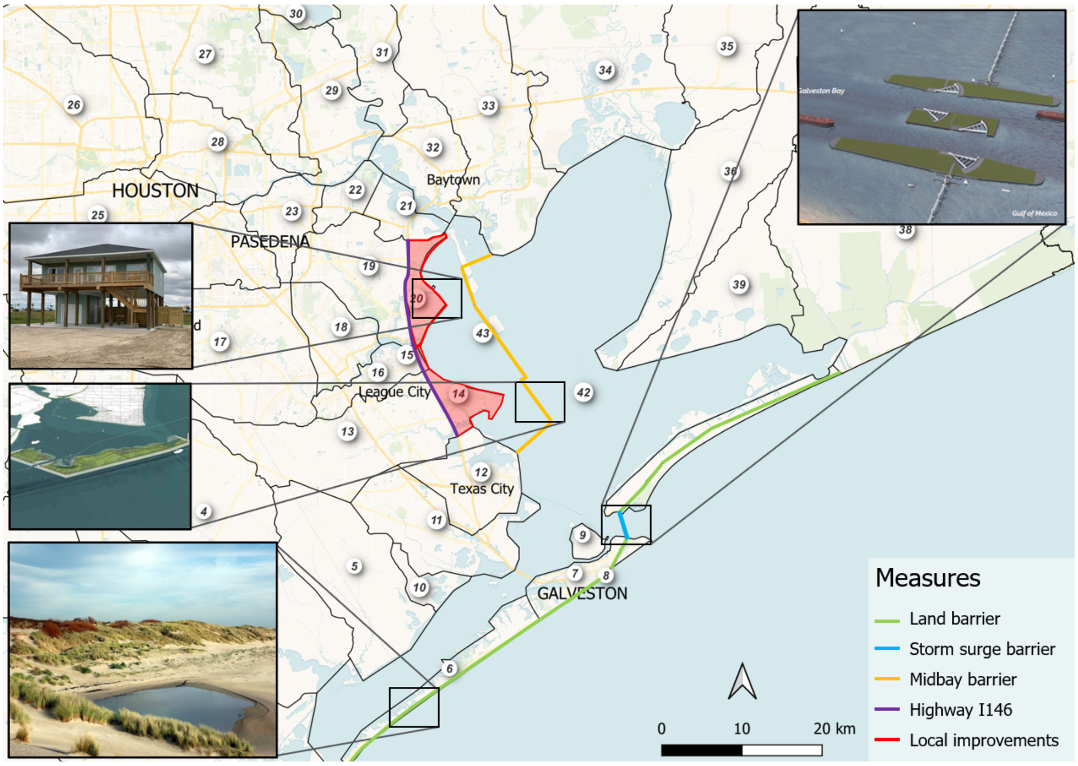


Figure 4.11: Locations of the measures considered in this study

Highway I146 Levee
Using the highway I146 as a levee to protect the underlying areas from flooding is one of the solutions proposed by the USACE to mitigate the residual risk in the bay. Again several levee heights will be tested in the model. The location of the highway is marked by the purple line in Figure 4.11. To be able to use this as a second line of defence, barriers are needed where the highway crosses Dickinson Bayou and Clear Creek. Because a large part of this measure is already constructed as part of the highway levee, the costs are expected to be low. However, unlike the midway barrier, this measure provides no protection to the areas directly along the west coast of the bay: basin 14, 15, 20. Furthermore, the Houston Ship Channel is also not protected by this measure. Additional measures will be needed for these unprotected areas.

The highway I146 levee can be implemented by increasing the border height between the adjacent basins. In this case, the border height between basins 16 and 15, 14 and 13, as well as basins 19 and 20. This prevents inter-basin flow between the two basins when the water level is lower than the crest of the levee. The height is set at 17 feet or 5.2 meters as suggested in the feasibility report (USACE, 2021b).

Elevating structures
Elevating structures above flood levels can prevent a large amount of flood damage. Elevated structures are already common practice in the area and are required for structures located in 100-year floodplains. However, as previously mentioned in Section 4.2.1, these floodplains are not always designated correctly. Because they are defined by a historical flood record and not a probabilistic assessment taking into account climate change and other changing conditions, they are often an under-representation of flood risk. Therefore, this measure will elevate all structures in basins 14, 15 and 20 up to the 100-year flood level plus 1 foot. Figure 4.11 shows the areas where structures would be elevated in blue. The heightening of structures is implemented by adapting the depth-damage curves used in the model for the chosen basins. The curve is shifted to the right by about 3 meters, which is the chosen level of elevation.

Buyouts
In a buyout, the government buys up properties and removes the present structures. The plot of land is then returned to nature. By performing buyouts, the value of a region lowers, and the damages occurring during a flood are lowered. Furthermore, by removing impervious surfaces, the infiltration capacity of the area increases, and more water can be stored without damaging properties. As mentioned in Section 4.2.2 more than 5000 properties remain on the buyout list of the HCFCD. These homes are located in areas where structural measures were deemed ineffective to reduce flooding or cost-prohibitive. Figure 4.11 shows the areas where buyouts are considered in blue. The effect of buyouts can be implemented by reducing the development value in the selected basins or contours. The same level of inundation will occur; however, the total damages in the basin or contour will be reduced.

Others
Some other measures were initially considered for the case study, such as preventing settlements, raising land, improving retention upstream, and improving infiltration upstream. However, these were ultimately not considered in the final study as the choice was made to focus on the structural measures. The Galveston Ring Barrier, which is a part of the USACE plan as well as the GBPP, is not included in this study as both plans contain it. Thus, to compare the differences between the two plans, it is not required to consider the Ring Barrier. Furthermore, the exact details of such a barrier are highly uncertain.

4.5.2. Estimating the costs of measures

To accurately determine whether a measure is cost-effective, the costs and benefits of the measure must be known. A change in the cost estimation can lead to a completely different, most effective outcome. However, it is notoriously difficult to estimate the construction costs of a project beforehand. Construction projects often finish behind schedule and over budget. Moreover, only a limited number of storm surge barriers have been built around the world, and their designs vary considerably.

The USACE (2021a) has provided a detailed estimate of the costs of the proposed plan. However, because not all of the measures considered in this thesis are part of the proposed plan, a different cost estimate for these measures would be needed. To keep the comparison between the measures fair, the same unit costs were used for all measures. These costs are split up per type of structural measure and based on completed projects in the US and internationally. Because these numbers are based on complete projects, unexpected costs are already included in the unit costs. The unit costs used in this study include construction, planning, engineering and construction management. Table 4.6 shows the unit costs used per element. Maintenance costs are left out of the analysis for this study but are recommended for further analysis.

Table 4.6: Unit costs per element based on completed projects (Jonkman & Lendering, 2021)

Element	Cost	Source	Bandwidth[3]
Storm surge barriers	2 – 4 M$/m [4]	International + US barriers	40%
Floodwalls (new)	19 – 30 M$/mile	New Orleans	35%
Raise coastal defence	10 M$/km per m raising	International	40%
Small flood gates	4 M$ per gate	New Orleans	30%
Nourishment's	50 $/m3 so 38 $/cyd	US experience	25%

Besides the structural flood defence measures aimed at keeping water out, there are also a few measures aimed at reducing the impact when flooding occurs. These mostly have a one-time cost associated with them for the initial construction. For example, after buying out properties once, there is no annual cost associated with the measure.
The costs of the measures were based on the unit costs listed in Table 4.6. The resulting costs of the measures used in the case study are listed in Table 4.7. For the structural measures, the costs are

[3] Indicative bandwidth based on project data
[4] Prediction formula (Kluijver et al., 2019)
[5] Average costs to raise a house above flood zone level in the U.S. (Olizarowicz, 2023)

Table 4.7: Costs of measures considered in the study

Name	Location (basins)	Type	Constant costs (Millions $/km)	Variable costs (Millions $/km/m)
Land barrier	Bolivar Islands	Structural	10	13
Storm surge barrier	Bolivar Roads	Structural	100	40
Midbay Barrier	Galveston Bay	Structural	20	20
Highway I146	Highway I146	Structural	10	10
Raising houses	14, 15, 20	Non-structural	725	0
Buyouts	14, 15, 20	Non-structural	2,200	0

provided as a constant cost per kilometre length of the structure and an additional variable cost per meter height per kilometre length of the structure. Non-structural measures only have a constant cost, which corresponds with the number of properties in the selected basins multiplied by the cost of raising a single property or value.

4.6. Model water surface elevation validation

Before the model can be used, its results must be validated. The maximum water surface elevation throughout the bay has been modelled by the SSPEED centre using proxy storm 036, as defined by FEMA. The hydraulic model is validated by comparing the results of the model to those of the SPPEED centre

1. No measures, base case with no additional defences implemented. Texas City Dike and the Galveston Seawall are the only structural measures.
2. The Coastal Spine, a single line of defence along the coast connecting Bolivar Peninsula, Galveston Island, Bolivar Roads and the Galveston Seawall. The land barrier and storm surge barrier are implemented at 6m crest elevation.
3. The Galveston Bay Park Plan, combined with the Coastal Spine, forms a secondary line of defence cutting through Galveston Bay. The land barrier, storm surge barrier and Midbay Barrier are implemented at 6m crest elevation.

Without any measures, the WSE reaches high levels throughout the bay and even higher levels in the Houston Ship Channel. Table 4.8 shows the results of the SSPEED centre model and FLORES model, as well as the difference between the two. For all locations, the difference is less than 8%. The damages calculated by the FLORES model for the proxy storm 036 are around $21 billion, however this is calculated using current property prices. The damage caused by Hurricane Ike is estimated at $27 billion (HCFCD, 2008). The difference between these damage estimates can be explained by inflation, as the calculated damages use recent property prices.

Table 4.8: Comparison results SSPEED and FLORES model, Storm 036, no measures

Location	WSE SSPEED (m)	WSE FLORES (m)	Difference
Galveston Pier	6.9	6.4	7 %
Texas City Docks	6.7	6.5	3 %
Dickinson Bayou	6.1	6.5	-7 %
Clear Lake	6.2	6.5	-5 %
Bayport	6.8	6.6	3 %
Houston Ship Channel	7.6	7.2	6 %

Table 4.9 shows the WSE calculated by the SSPEED centre and FLORES model with the Coastal Spine in place. In FLORES, this was modelled using a land barrier and storm surge barrier at a height of 6m. The difference becomes more pronounced compared to the baseline situation. The effect of wind setup inside the bay, which leads to higher WSEs in the Houston Ship Channel, is underestimated by the FLORES model. Similarly, the WSE at the Galveston Pier location increases with the Coastal Spine in place. This increase is not present in the FLORES results.

Table 4.9: Comparison results SSPEED and FLORES model, Storm 36, Coastal Spine (6m)

Location	WSE SSPEED (m)	WSE FLORES (m)	Difference
Galveston Pier	7.5	6.4	14%
Texas City Docks	5.0	3.7	26%
Dickinson Bayou	4.1	3.7	9%
Clear Lake	4.0	4.1	-2%
Bayport	4.4	3.8	15%
Houston Ship Channel	5.0	3.8	25%

Table 4.10 shows the WSE calculated by the SSPEED centre and FLORES model with the Coastal Spine and GBPP in place. In FLORES, this was modelled using a land barrier, storm surge barrier and Midbay Barrier at a height of 6m. The WSE behind the Midbay Barrier in the lower 4 locations is modelled well. However, the FLORES model struggles again with the setup effect at the Texas City Docks, which leads to a difference of 30% in this location.

Table 4.10: Comparison results SSPEED and FLORES model, Storm 36, Coastal Spine and GBPP (6m)

Location	WSE SSPEED (m)	WSE FLORES (m)	Difference
Galveston Pier	7.5	6.4	14%
Texas City Docks	5.5	3.8	30%
Dickinson Bayou	3.2	3.0	8%
Clear Lake	3.2	3.0	5%
Bayport	3.2	3.0	7%
Houston Ship Channel	3.2	3.0	7%

Overall, the FLORES model's simulation results of the water surface elevation in Galveston Bay are deemed sufficiently accurate for the preliminary design phase of the project. However, a detailed analysis is required for further design of a flood protection system.

5 Case study results

This chapter presents the results of the case study performed in the Galveston Bay area, following the framework outlined in Figure 3.1 of Chapter 3. It aims to answer local policymakers' questions and identify possible adaptation pathways. Firstly, the current flood risk is analysed in Section 5.1. Secondly, screening setup and results are discussed in Section 5.2. Thirdly, the screening results are analysed in two ways in Section 5.3. First, the questions posed by local stakeholders are answered based on the screening results, and later on, a broad analysis of the entire screening is performed. Next, in Section 5.4, adaptation pathways are constructed based on tipping points and policy option cut-offs. Lastly, the results of the case study are summarised and evaluated in Section 5.5.

5.1. Analysis of current flood risk

Two drivers contribute to flooding in the area: storm surge and runoff (caused by rainfall). Both are defined by their 0, 10, 100 and 500-year return periods. Table 5.1 shows the flood damages caused by all possible combinations of storm surge and rainfall events. This table shows that the storm surge component is the biggest driver of damages. In a 500-year rainfall event, $670 million in damages are expected. In contrast, the 500-year storm surge event would lead to $22,492 million in damages. Thus, the flooding due to rainfall is insignificant compared to the storm surge. Besides this, the system shows strange behaviour when extreme rain and storm surges occur at the same time. In the 500-year storm surge and rainfall event, the expected damages are lower than for the 500-year storm surge and 0-year rainfall event. Figure 5.1 shows the risk profile of the current situation for the storm surge component because the storm surge event is the key driver of flood damages. A risk profile describes the relation between an event's annual probability of occurrence and its associated damages. Both axes contain a logarithmic scale; the expected damages increase as the probability decreases for more extreme events. By integrating the area under the curve, the risk can be found. The rest of the report calculates the risk in this manner.

5.2. Galveston Bay screening

5.2.1. Screening set up

Some definitions used in this report should be repeated before discussing the results:

Table 5.1: Flood damages for different combinations of rainfall and storm surge events (millions)

Rainfall RP	**Storm surge RP**			
(years)	0	10	100	500
0	$ 65	$ 6,124	$ 14,645	$ 22,492
10	$ 104	$ 6,810	$ 14,815	$ 21,789
100	$ 324	$ 6,978	$ 14,630	$ 21,838
500	$ 670	$ 7,594	$ 15,129	$ 21,627

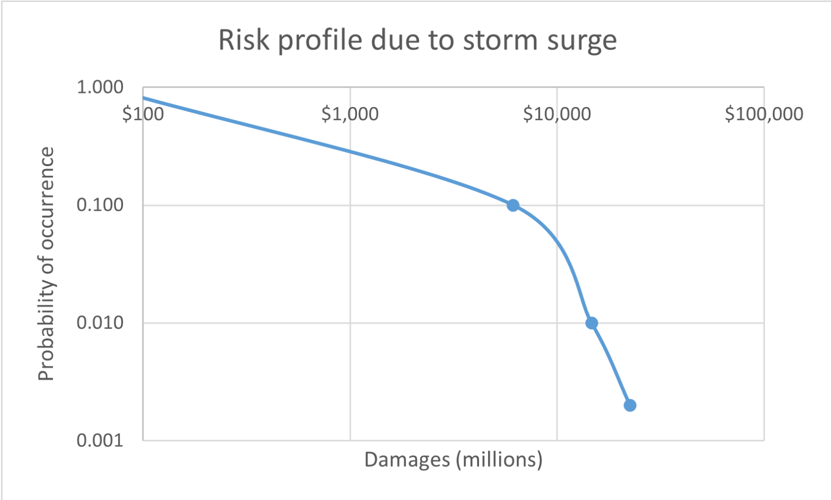


Figure 5.1: Risk profile for storm surge events. Rainfall set to 0.

- A scenario is a combination of the climate and development scenario used in the model for that particular run.
- A flood risk reduction strategy is a (set of) measure(s) from the list defined in Section 4.5.1 implemented in that particular run.
- The hydraulic boundary conditions are defined by their return periods and consist of storm and rainfall conditions. These are characterised by their 0, 10, 100 and 500-year return period (RP) storm surge and 24-hour precipitation, respectively.
- For one experiment, the model chooses one scenario and one set of measures and evaluates these for all combinations of hydraulic boundary conditions. Afterwards, a risk curve is constructed based on the expected damages per RP. By integrating the area under the curve, the risk is found. Each experiment returns the risk, construction costs, and number of people affected by flooding annually for the chosen strategy.
- The risk reduction is calculated by comparing the risk of a screening run with a measure in place to the baseline.
- The risk reduction is translated to a net present benefit by assuming a lifetime of 40 years and a discount rate of 2.5%. The net present benefit, combined with the construction costs, gives the benefit-cost ratio.

The screening is limited to 3300 experiments. This is a trade-off between computation time and covering as much of the solution space as possible. All 12 scenarios were included, three development and four climate scenarios, which means 3300/12 = 275 strategies were considered. In total, four binary measures and one ternary measure were considered. Thus, $2^4 * 3 = 48$ strategies can be formed, leading to $275/48 = 5.7$ variations in the height of the structural measures per strategy.

The results are analysed using a few different methods, both in the FLORES tool and self-developed. Section 3.4 provides more information on how these analyses work.

- Feature Scoring analysis can identify the influence of the model's input parameters on the output parameters. Significant parameters can easily be separated from insignificant parameters. The measures and scenarios considered are listed on each plot's left side, and the outcomes are listed at the bottom. The value and colour of the box intersected by two parameters indicate the degree of correlation between the two. A high number and more yellow colour indicates a high degree of correlation.
- PRIM analysis shows the values of the input parameters required to obtain the pre-specified condition of the output variable. This clarifies which factors contribute to a particular value of one or more output variables. More information on the PRIM is available in Section 3.4 of the report.

- Scatter plots plot all or a subset of the experiments as individual dots on a 2D plot. The size of these dots can then be scaled according to a third output variable and grouped by colour according to one of the input variables.

5.2.2. Screening results

Table 5.2 shows the results of the baseline screening. These are the screening results where no measure has been applied. Risk in the current situation is calculated as $4,111 million per year. However, in the growth and RCP8.5 climate scenario, this can triple to $12,787 million per year. Thus, the effect of the climate and development scenario on risk is significant. Risk is defined as the probability of flooding multiplied by the consequences of flooding and is expressed as dollars/year.

Table 5.2: Baseline screening results without additional measures

ID	Climate scenario	Development scenario	Risk (Millions/yr)	Affected population (thousands/yr)
1	Current	DP2	$ 2,878	63
2	RCP1.9	DP2	$ 3,835	84
3	RCP4.5	DP2	$ 4,108	91
4	RCP8.5	DP2	$ 5,265	111
5	Current	Current	$ 4,111	89
6	RCP1.9	Current	$ 5,478	120
7	RCP4.5	Current	$ 5,869	130
8	RCP8.5	Current	$ 7,522	159
9	Current	DP1	$ 6,989	152
10	RCP1.9	DP1	$ 9,313	204
11	RCP4.5	DP1	$ 9,977	222
12	RCP8.5	DP1	$ 12,787	270

For example, the damages and affected population are compared for the 1 in 100-year storm and 1 in 100-year rainfall event under the current climate change and development scenario. Figure 5.2 shows the baseline flood map of Galveston Bay, meaning without any measures applied. Figure 5.3 shows the flood map of Galveston Bay when a land and storm surge barrier of 6 meters high is in place. An apparent reduction in flooded areas is visible when comparing both images. In the base case, inundation depths reach up to 6 meters. In contrast, inundation is limited to 2 meters with the barriers in place. Especially the valuable west coast of the bay sees dramatically less flooding. The east and northwest sides still see flooding due to the low and flat, marsh-like terrain flooding due to runoff.

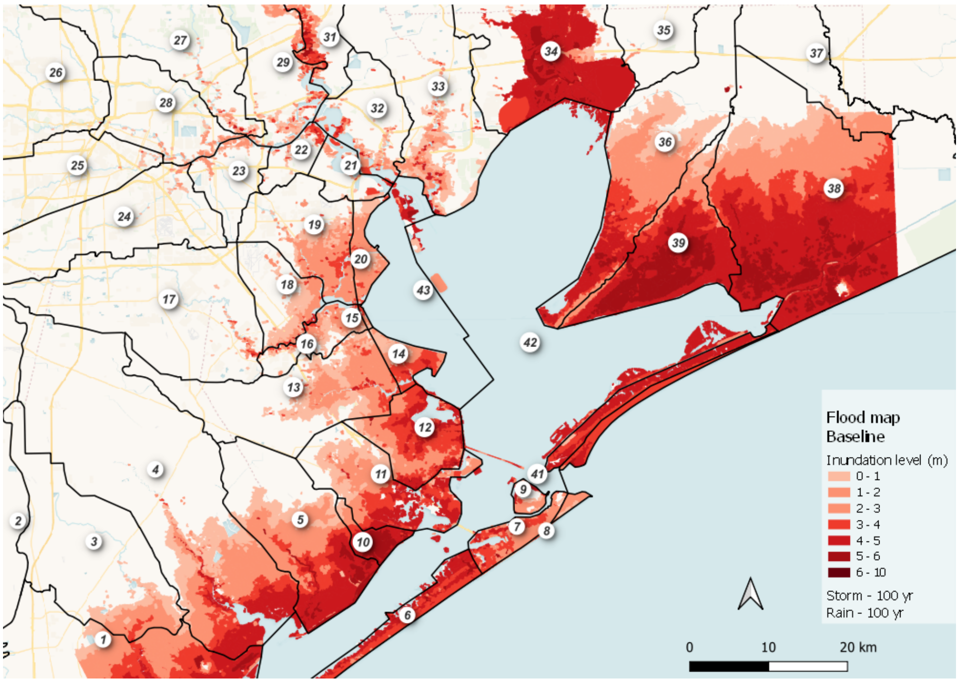


Figure 5.2: Flood map of Galveston Bay in the current scenario with no measures applied, subject to the 1 in 100-year storm surge and 1 in 100-year rainfall event.

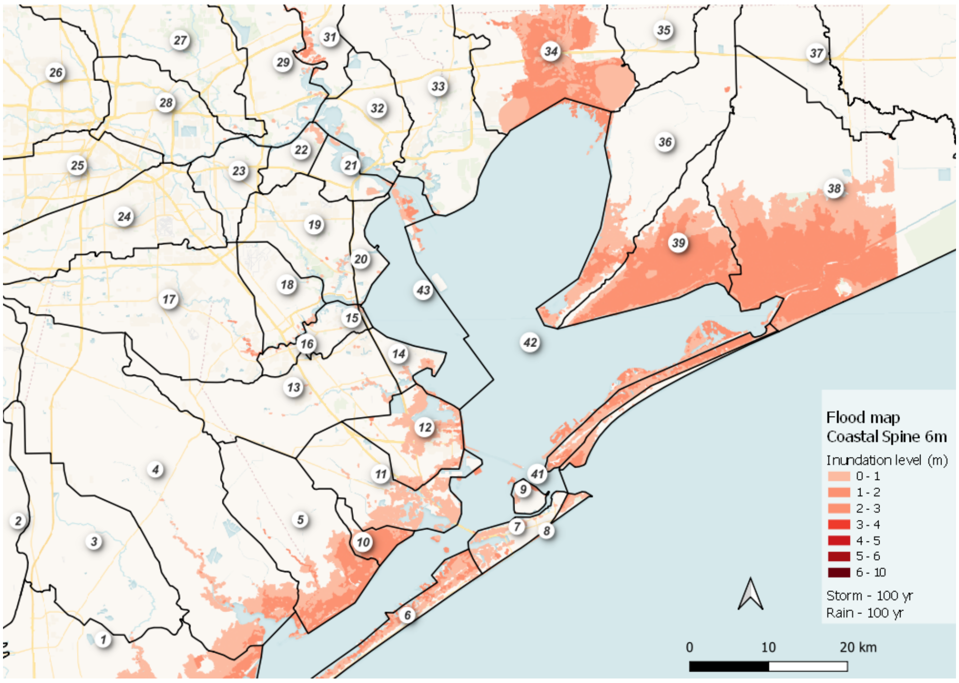


Figure 5.3: Flood map of Galveston Bay in the current scenario with a land barrier and storm surge barrier of 6 meters crest elevation implemented, subject to the 1 in 100-year storm surge and 1 in 100-year rainfall event.

Table 5.3 shows the expected damages for both simulations. For this particular event, a damage reduction of 4.2 billion dollars, from 7 to 2.8 billion dollars, was achieved. The residual damages are expected to be slightly overestimated, as most damage occurs in low-lying areas like the Bolivar Peninsula and Galveston Island. Here, residential properties are often already raised, which is not modelled in this study.

Table 5.3: Comparison of damages and affected population when implementing the Coastal Spine for the 1 in 100-year storm and 1 in 100-year rainfall event.

	Damages (millions)	Costs (millions)	Affected population
Baseline	$ 6,977	$ -	162,000
Coastal Spine	$ 2,778	$ 8,210	64,000

5.3. Analysis of screening results

5.3.1. Answers to questions posed by local stakeholders

This section aims to answer questions posed by local stakeholders, using relevant data and analysis methods for each question specifically. These questions were obtained from Prof. Bas Jonkman.

What single measure leads to the highest flood risk reduction?

Figure 5.4 shows the results of the feature scoring analysis of the global screening, thus with all measures, climate and development scenarios considered. From the figure, it becomes clear that implementing the land barrier on the barrier islands has the largest influence on the risk reduction and reduction of the affected population. Only the effect of the development scenario is significant when compared to the effect of the land barrier. This means the land barrier provides the largest flood risk reduction of all measures considered in this research.

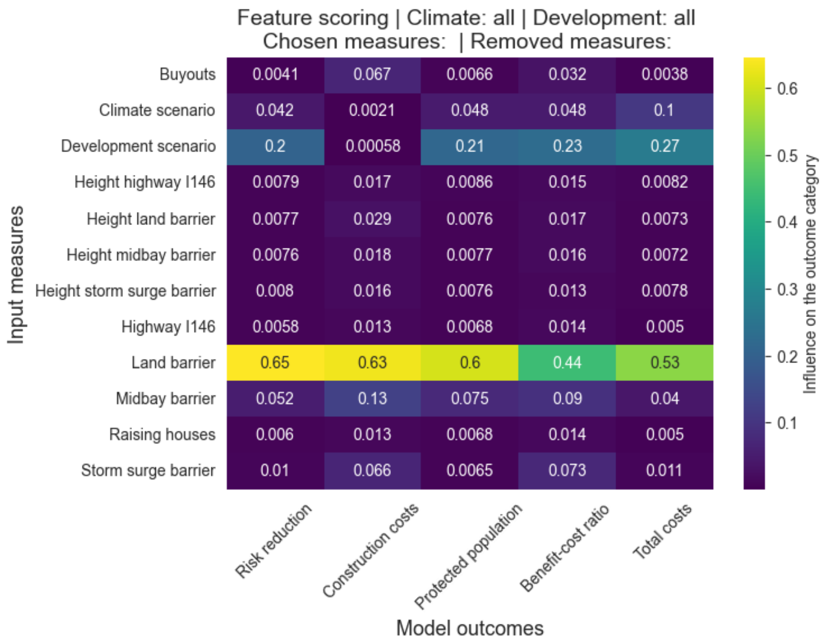


Figure 5.4: Feature scoring shows a significant dependency on implementing the land barrier at the location of the barrier islands. Larger numbers and yellow colour indicate a dependency, while dark blue means independent.

How does implementing the land barrier affect the expected flood risk?

For the 1 in 100-year storm surge event, a 6-meter high land barrier reduces the expected flood damage of the study area by 78%. When considering all combinations of storm surge and rainfall events, the risk reduction lies around 75%. In the same 1 in 100-year storm surge event, a 4-meter high land barrier only reduces the expected flood damage of the study area by 46%.

Figure 5.5 shows the height of the land barrier and the associated benefit-cost ratio for a range of heights and several climate scenarios. The economic optimum generally seems to prefer lower crest elevations in all cases. A slight shift in the curve is visible when comparing the climate scenarios. This indicates that a higher crest elevation is optimal in the RCP8.5 scenario, which makes sense considering the sea level rise in this scenario. A crest elevation of around 4 meters does have drawbacks in terms of the population's protection level. Figure 5.6 shows the impact of the height of the land barrier on the reduction in the affected population. Although the effect is limited in the current development scenario, a higher crest elevation is important for the higher climate change scenarios. In the RCP8.5 scenario, 30 thousand fewer people are protected when comparing a 7-meter-high dike to a 4-meter-high dike. A trade-off must be made between the economic optimum and the safety level of the population.

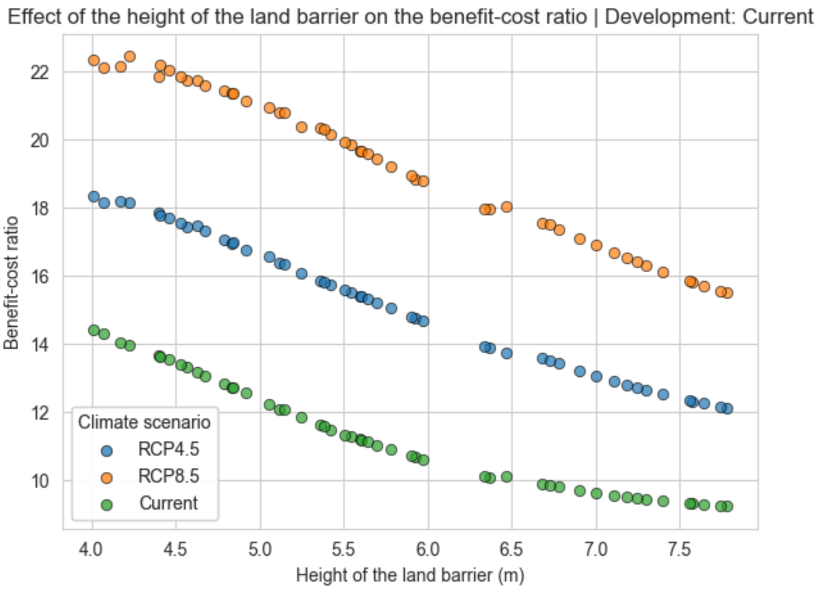


Figure 5.5: The benefit-cost ratio of implementing the land barrier at various heights.

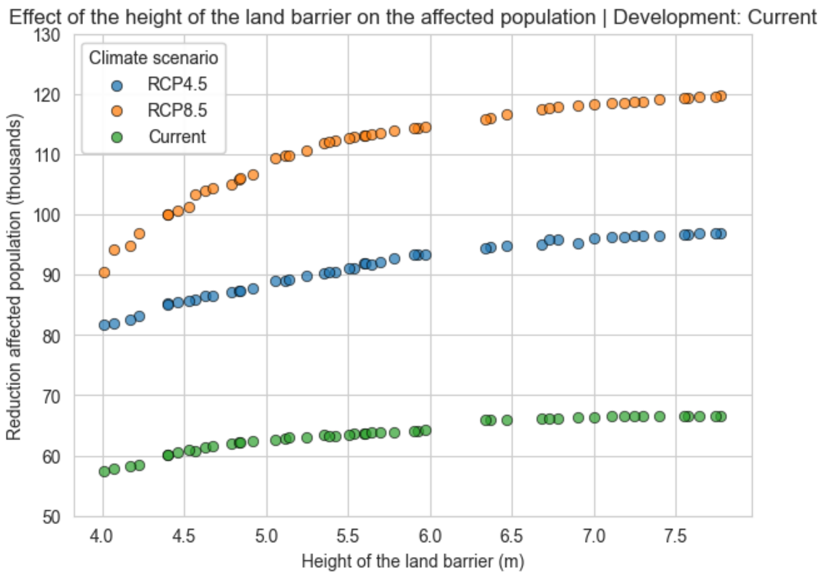


Figure 5.6: Reduction of the affected population by implementing the land barrier at various heights.

How effectively can the flood risk be managed with or without the Bolivar Roads storm surge barrier?

Figure 5.7 below shows how implementing the storm surge barrier at Bolivar Roads affects risk reduction and construction costs. Two distinct effects can be seen in the figure. All experiments on the right of the red line contain the land barrier as a measure; all experiments on the left of the line do not. On the right-hand side, construction costs do rise somewhat with the implementation of the barrier. However, the risk is also reduced accordingly. Interestingly, the benefit-cost proposition does not change significantly with the addition of the storm surge barrier. Common sense suggests that the closure of the gap in the coastal spine would increase the benefit-cost ratio, as it would prevent the storm from pushing water up into the bay and raising the water level inside the bay. However, when observing the two point clouds on the right side of Figure 5.7, the benefit-cost ratio (B/C) does not improve when implementing the storm surge barrier. The lack of an improved benefit-cost ratio could be due to a flaw in the hydraulic modelling or a disproportionately high cost for the storm surge barrier. Looking at the left-hand side of the figure, the risk reduction does not increase substantially when implementing the storm surge barrier without the land barrier. This is most likely due to the low elevation of the barrier islands easily being overtopped and the storm surge barrier circumvented.

To conclude, the storm surge barrier should be implemented along with the land barrier to obtain the highest level of protection and risk reduction. However, implementing just the land barrier or the Midbay Barrier can achieve a similar benefit-cost ratio. If maximising the benefit-cost ratio is desired, only building the land barrier and no storm surge barrier is preferred.

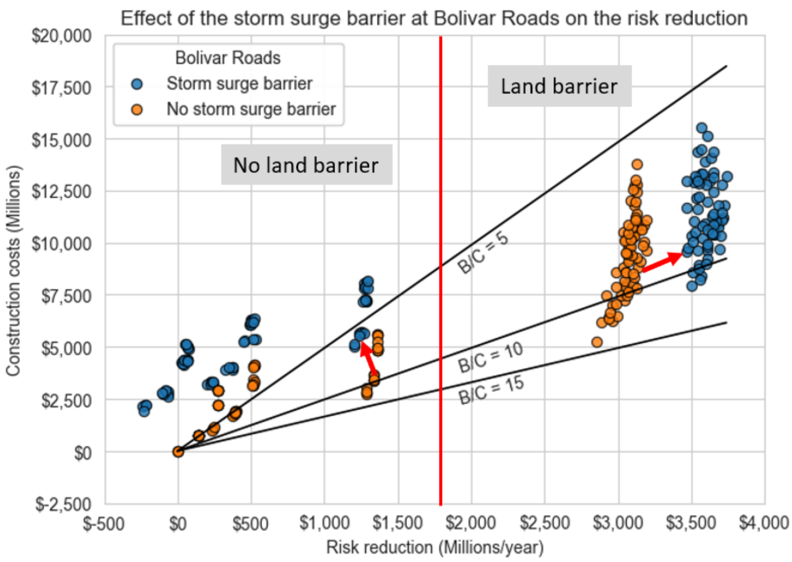


Figure 5.7: Scatter plot showing the effect of the storm surge barrier at Bolivar Roads, each dot is one experiment, and only the current development scenario is shown. All experiments on the right of the red line contain the land barrier; all experiments on the left of the line do not.

How does climate change affect the flood risk management strategy?
The climate change scenarios are implemented in the model using the sea level, wind velocity, and rainfall intensity parameters. These, in turn, affect the storm surge level, wind setup inside the bay, loading on structural elements, and more, increasing the probability of flooding. When the probability of flooding increases, the effectiveness of measures decreases. For example, raising houses becomes less effective as the sea level rises, and even the raised houses will flood more often. On the other hand, flooding is irrelevant once properties are bought out and does not cause damage. To illustrate this, when the climate change scenario progresses from the current scenario to the RCP8.5 scenario, the benefit-cost ratio of buyouts changes from 3.15 to 6.58. Meanwhile, for raising houses, the ratio changes from 5.01 to 6.77. Thus, raising houses and buyouts achieve the same level of cost-effectiveness when the climate change scenario RCP8.5 is expected.

How does the region's development affect the flood risk management strategy?
The development scenarios implemented in the model affect the area's total property value and population. The costs of structural measures are not directly affected by the value they protect, but the

benefits from preventing a flood event do rise. Thus, the benefit-cost ratio will increase if the property value behind the measure increases. A higher benefit-cost ratio makes previously unattractive measures more attractive to implement. Table 5.4 shows the effect of the development scenario when a land barrier of 4.4m is implemented. The benefit-cost proposition changes substantially from around 10 in the DP1 (shrinkage) scenario to around 23 in the DP2 (growth) scenario.

Table 5.4: Effect of the development scenario on the risk reduction and benefit-cost ratio. Land barrier with crest elevation 4.4m implemented, current climate scenario.

	Risk reduction (millions/yr)	Construction costs (millions)	Benefit-cost ratio
DP2	$ 1,999	$ 5,222	9.6
Current	$ 2,855	$ 5,222	13.7
DP1	$ 4,854	$ 5,222	23.3

Figure 5.8 shows the distribution of experiments grouped by development scenario. The points connected by the red arrows all represent the implementation of the 4.4m high land barrier. The points are spread on the horizontal axis, not the vertical axis. Risk reduction does change by increasing the potential benefits of measures, however the construction costs stay the same for at least the structural measures. In general, measures tend to become substantially more effective when growth continues.

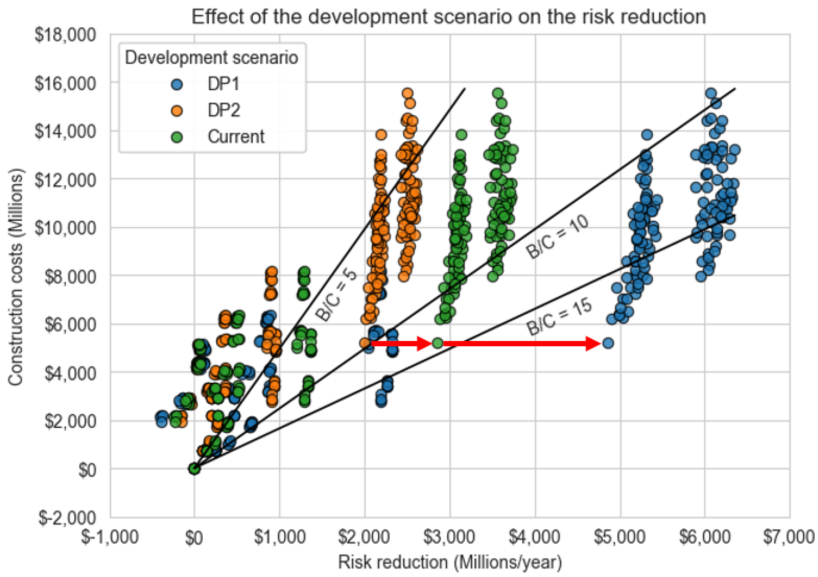
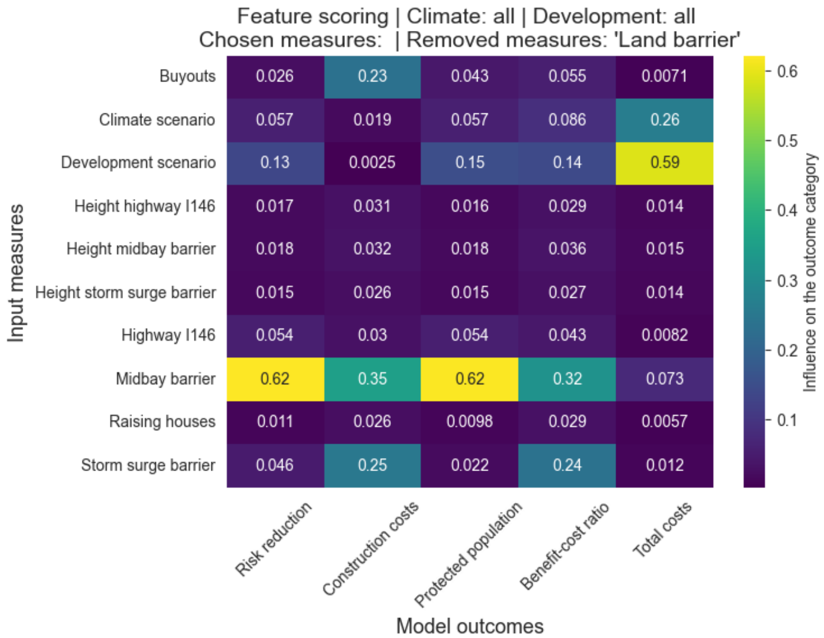


Figure 5.8: Scatter plot showing the effect of the selected development scenario, each dot is one experiment

How can the region be protected from flooding without the land barrier?

If the land barrier is not implemented, the feature scoring analysis changes significantly. Figure 5.9 shows the results of the feature scoring analysis where all experiments containing the land barrier have been excluded. It becomes clear that the Midbay Barrier has the largest influence on risk reduction. The effect of all other measures is insignificant in comparison. Figure 5.10 shows the effects of the possible secondary lines of defence when the land barrier is excluded. The Midbay Barrier results in a higher risk reduction and larger benefit-cost ratios than solutions without it. With these results, there is no substantial benefit to implementing Highway I146. Notably, in some cases, the risk reduction becomes negative. This result is caused by an anomaly in the numerical calculations of the hydraulic model of FLORES. In some cases, this leads to short spikes in the water level of a basin. The spike is recorded as the maximum water level elevation, which causes the basin's damages to significantly increase.



	Risk reduction	Construction costs	Protected population	Benefit-cost ratio	Total costs
Buyouts	0.026	0.23	0.043	0.055	0.0071
Climate scenario	0.057	0.019	0.057	0.086	0.26
Development scenario	0.13	0.0025	0.15	0.14	0.59
Height highway I146	0.017	0.031	0.016	0.029	0.014
Height midbay barrier	0.018	0.032	0.018	0.036	0.015
Height storm surge barrier	0.015	0.026	0.015	0.027	0.014
Highway I146	0.054	0.03	0.054	0.043	0.0082
Midbay barrier	0.62	0.35	0.62	0.32	0.073
Raising houses	0.011	0.026	0.0098	0.029	0.0057
Storm surge barrier	0.046	0.25	0.022	0.24	0.012

Figure 5.9: Feature scoring analysis where all experiments with the land barrier have been removed. The Midbay Barrier becomes the most effective solution to reduce risk.

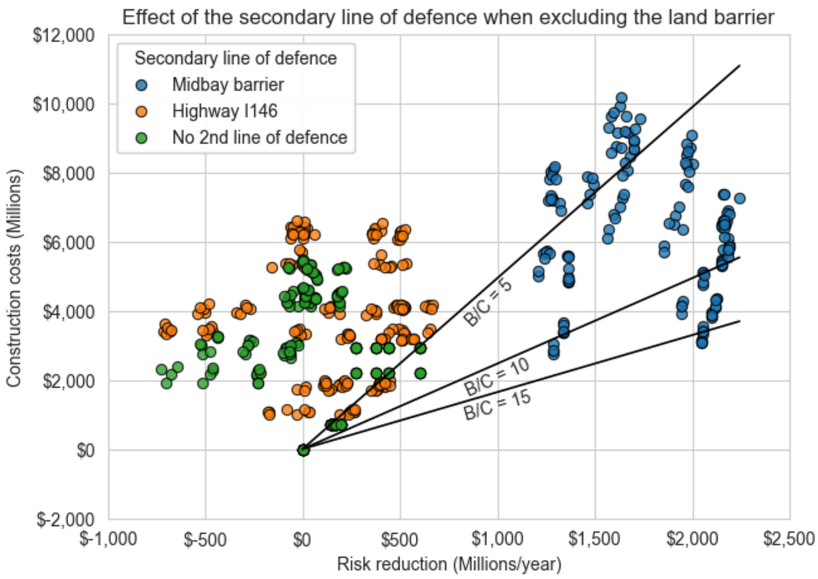


Figure 5.10: Scatter plot showing the effects of the secondary line of defence when experiments containing the land barrier are excluded.

In what situation is it effective to build the Midbay Barrier before the land barrier?
Large and costly projects need substantial time for ideas to form, develop, funding to be appropriated, permits granted and finally constructed. These projects can take decades to come to fruition. However, the risk of devastating floods is present every year during each hurricane season. Therefore, it is imperative to reduce the risk as soon as possible. Smaller and shorter lifespan measures can be the solution for this intermediate gap in protection. To make a well-considered choice, information is needed on the payback period for these measures and how they affect each other.

The estimated construction costs of the Midbay Barrier are $2,735 million and, in the current scenario,

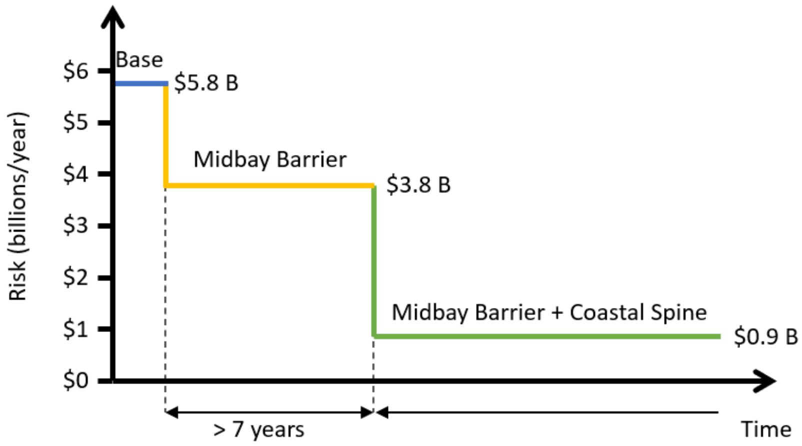


Figure 5.11: Timeline for implementing the Midbay Barrier before the Coastal Spine in a cost-effective manner.

provide a risk reduction of $1,286 million per year to the area. Within 3 years, the measure would provide a return on investment. Just achieving break even does normally not make sense for government projects as there are often better ways to spend funds. Therefore, a minimum benefit-cost ratio of 3 is required in this study. By calculating the net present value of the benefits using a discount rate of 2.5%, a benefit-cost ratio of 3 is found after 7 years. Thus, the Midbay Barrier would be a cost-effective measure if the time frame to design and construct the Midbay Barrier is at least 7 years shorter than the time required for the design and construction of the Coastal Spine. Figure 5.11 shows a timeline of the risk development for this scenario. Lastly, variation in costs of measures has a significant impact on the payback period and, thus, the value proposition of these strategies. More detailed cost estimations are advised.

5.3.2. Results of the broad screening

This section aims to analyse the complete system. The analysis starts at a system level, examining the most effective risk reduction strategies and the effects of different scenarios. Then the analysis narrows down to the specific measures and combinations of measures. Figure 5.12 shows the feature scoring analysis of the complete area with all measures and scenarios included. Input measures are listed on the left, and output parameters are on the bottom. The number on the intersection of a measure and output indicates the degree of correlation between these parameters. A high number and yellow colour indicate a high degree of correlation. From the figure it becomes clear that the land barrier on the barrier islands has the largest effect on all outcome parameters, indicated by the yellow colour and the high correlation numbers compared to the other measures. Its effects overshadow the effects of all other measures and thus lead to the largest risk reduction and benefit-cost ratio. Also notable is the effect of the development scenario on the risk reduction and benefit-cost analysis. This indicates the large effect economic and population growth can have on the risk analysis and highlights the importance of development regulations in flood-prone areas.

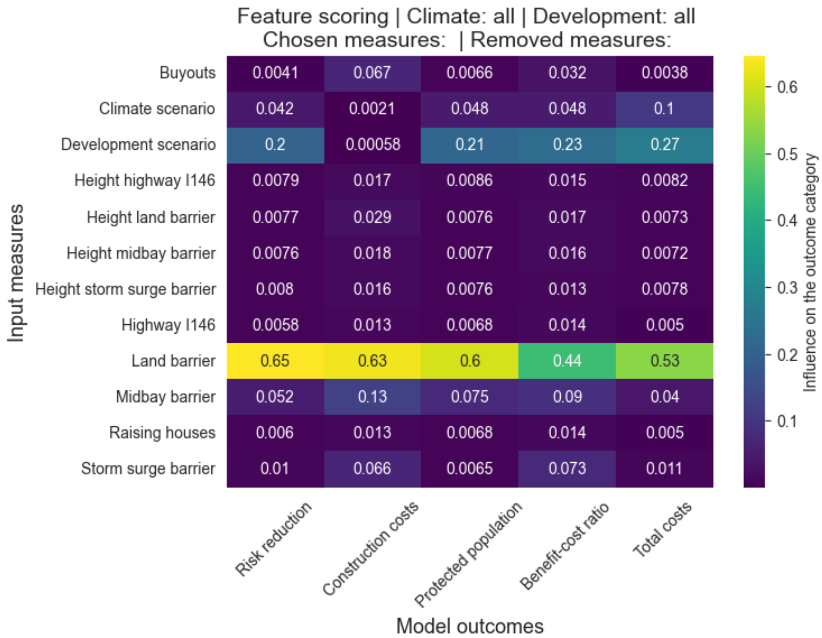


Figure 5.12: Feature scoring shows a significant dependency on implementing the land barrier at the location of the barrier islands. Larger numbers and yellow colour indicate a dependency, while dark blue means independent.

Figure 5.13 shows the feature scoring results where the land barrier is implemented, and the climate and development scenarios are set to the current levels. The storm surge barrier at Bolivar Roads is clearly the most effective solution to reduce the risk when the land barrier is implemented. Although the storm surge barrier hardly influences the benefit-cost ratio. This indicates that the benefit-cost ratio of the storm surge barrier, combined with the land barrier, is roughly the same as the benefit-cost ratio of the land barrier on its own.

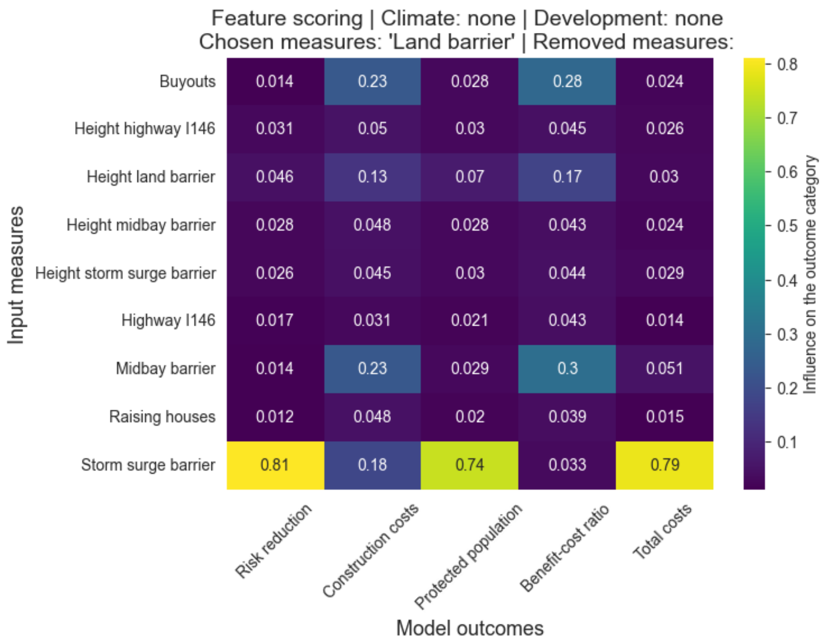


Figure 5.13: Feature scoring with the land barrier at the location of the barrier islands implemented for the current climate and development scenario. Implementing a storm surge gate at Bolivar Roads has the largest influence on risk reduction.

Figure 5.14 shows the results of the feature scoring analysis where the complete coastal spine is implemented, consisting of the land barrier and storm surge barrier at Bolivar Roads. With these measures implemented, the biggest influence on reducing the flood risk further is the height of the dike. Implementing the Midbay Barrier or increasing the height of the storm surge barrier both have a moderate effect on risk reduction. However, implementing the Midbay Barrier is not advisable as the effect on the construction costs is larger, which means the benefit-cost ratio actually lowers. A secondary line of defence thus leads to a higher level of protection but is less cost-effective than a singular line of defence. Especially if the goal is to protect a large number of the population, increasing the height of the land barrier and storm surge barrier is most beneficial. Figure 5.6 shows a similar result. Increasing the height of the land barrier becomes even more important in the RCP8.5 scenario.

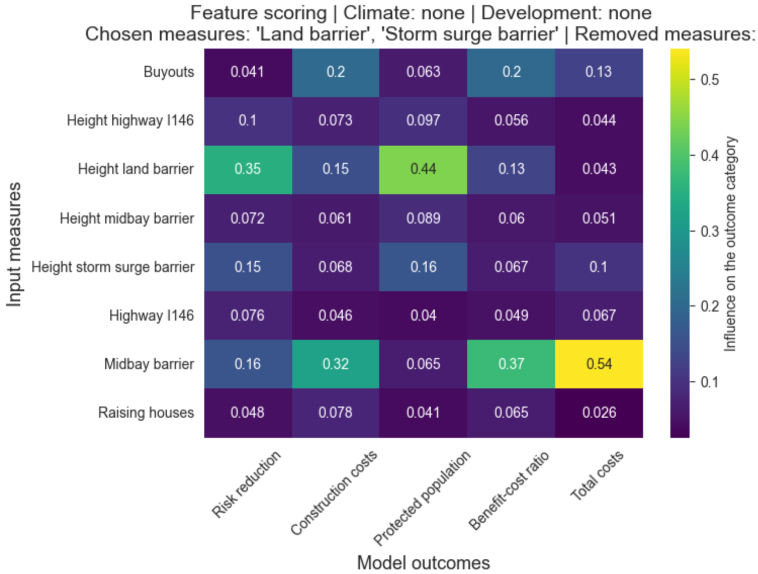


Figure 5.14: Feature scoring with a complete coastal spine implemented. The height of the dike and storm surge barrier have the largest influence on risk reduction.

Figure 5.15 shows the feature scoring when the land barrier is removed from the results. In this case, the Midbay Barrier provides the largest risk reduction, and all other measures are insignificant.

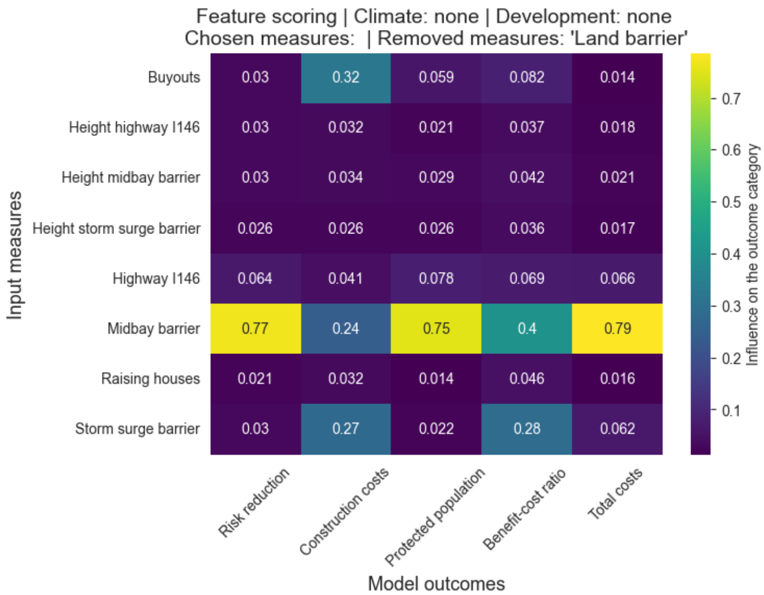


Figure 5.15: Feature scoring with the land barrier removed. Implementing the Midbay Barrier has the largest effect on reducing the residual risk

5.4. Adaptation pathways for Galveston Bay

5.4.1. Identification of tipping points and policy options cut-offs

Before the adaptation pathways themselves can be constructed, the tipping points must be identified. A tipping point is a point where a measure is no longer able to fulfil the objective. This can be due to changing boundary conditions such as climate change or development. One way to identify these tipping points is by using PRIM analysis, as covered in Section 3.4. In short, PRIM analysis shows which input variables lead to the desired output variables. Effectiveness, in this thesis, has been defined as achieving a benefit-cost ratio of 3 or greater. Measures with a lower benefit-cost ratio are likely not attractive for governments to invest in.

Figure 5.16 shows the result of a single PRIM analysis in the current climate and development scenario under the condition of a benefit-cost ratio smaller than 3. In this case, it is easier to start with identifying measures that do not meet the criteria. The value right of the measure name lists the quasi-p-value, or qp value. A smaller qp value indicates a larger correlation. The qp value has to be lower than 0.05 to be significant. The figure shows that not implementing the land barrier and implementing the storm surge barrier is the most important contribution to a low benefit-cost ratio. By repeating this PRIM analysis for different development and climate change scenarios, it is possible to identify where measures become effective or ineffective. Appendix C contains all the PRIM analysis results to identify the tipping points of measures for the different scenarios.

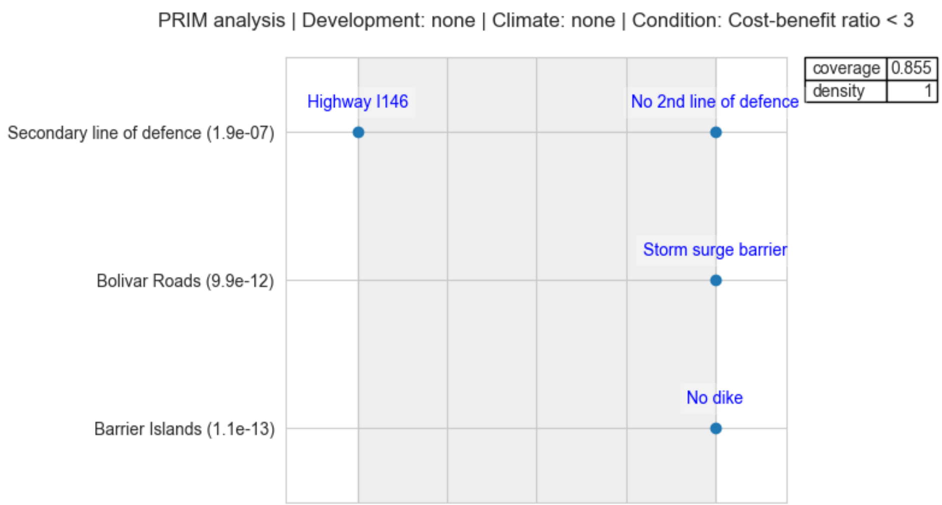


Figure 5.16: PRIM analysis for the current development and climate scenario under the condition benefit-cost ratio is smaller than 3. Implementing the storm surge barrier leads to low benefit-cost ratios.

The following tipping points have been identified through the PRIM analysis:

- The land barrier on the barrier islands is always an effective measure
- The storm surge barrier is only effective in combination with the land barrier
- The Midbay Barrier is always effective
- Highway I146 is only effective in the DP1 scenario for the current and RCP1.9 climate scenario
- Raising houses is always effective
- Buyouts are effective in the DP1 scenario, the current development scenario from RCP1.9 onwards, and in the DP2 scenario from RCP4.5 onwards

5.4.2. Adaptation pathways of the growth development scenario

Based on the tipping points and results of the broad screening, the effectiveness regions for the various measures are identified. Figure 5.17 shows the effectiveness regions of the measures for the growth development pathway (DP1). The figure shows how the storm surge barrier is ineffective when built independently and how highway I146 is only effective until the RCP1.9 scenario. Also, the current situation is marked in grey and leads to a dead end, indicating that the system objective is currently not met. Again, ineffective is defined as a benefit-cost ratio smaller than 3.

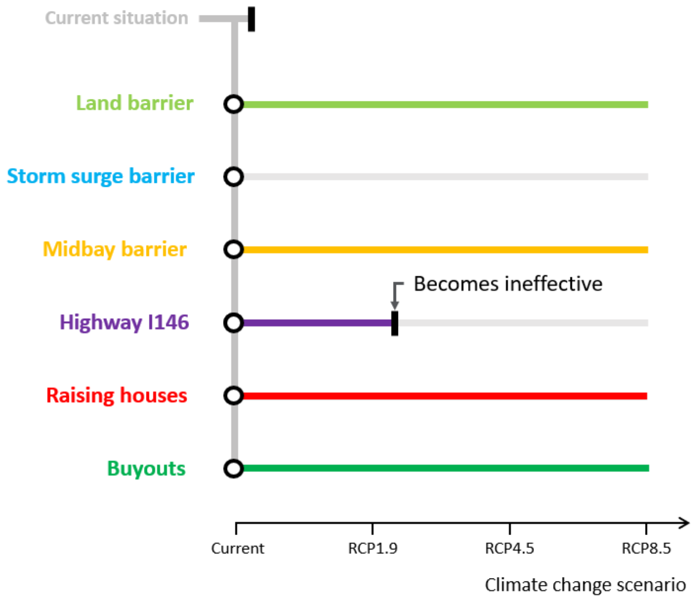
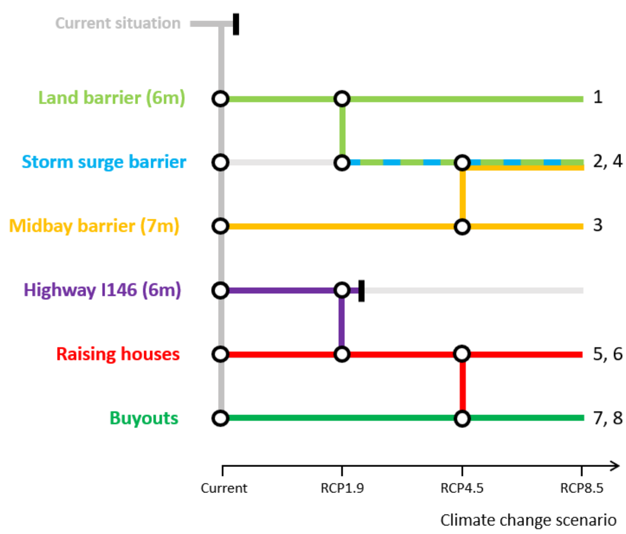


Figure 5.17: Effectiveness regions for the growth development scenario (DP1)

Next, the pathways themselves are formed by combining measures. Only the interesting and/or relevant pathways are shown. More combinations are possible, but these are left out for clarity. Figure 5.18 shows the pathways map and scorecard for the DP1 (growth) scenario. From the effectiveness regions, it has become clear that four measures are effective on their own until the RCP8.5 scenario; these measures are represented by pathways 1, 3, 6 and 8. Furthermore, some logical combinations of measures can be made. Firstly, the land barrier is combined with the storm surge barrier to complete the coastal spine concept, which is represented by pathway 2. Secondly, building the Midbay Barrier and later implementing the Coastal Spine (as discussed in Section 5.3.1) is represented by pathway 4. Thirdly, the building of the Highway I146 levee and the protection of the outer basins by raising houses are represented by pathway 5. Lastly, raising houses and switching to buyouts is represented by pathway 7.



Pathway	Costs Millions $	Benefit Millions $/year	Benefit/ Cost	Protected population Thousands/year
1	7,699	7,264	23.7	160
2	9,259	8,258	22.4	173
3	3,545	3,491	24.7	102
4	12,202	8,325	17.1	180
5	1,909	391	5.1	1
6	725	284	9.8	0
7	2,926	750	6.4	19
8	2,200	750	8.6	19

Table values for the RCP4.5 scenario

Figure 5.18: The adaptive pathways map and scorecard for the growth development scenario (DP1)

On the right-hand side of the pathways map is the scorecard for the pathways. Here, construction costs, annual benefits, benefit-cost ratio, and protected population are listed for each pathway. For the benefit-cost ratio, all measures are assumed to have a lifespan of 40 years and an interest rate of 2.5%, as prescribed by the USACE. The numbers in the scorecard are taken from the RCP4.5 climate change scenario, as this is the most likely scenario to occur in the next 40 years. By observing the scorecard, it becomes clear how the benefits of the first 4 pathways largely overshadow the last 4 pathways. The land barrier and Midbay Barrier provide substantial protection to large areas, while raising houses, Highway I146 and buyouts are of a smaller scale and protect a specific area. Furthermore, the benefit-cost ratio of the first 4 pathways is substantially larger than the latter. Interestingly the Midbay Barrier provides a similar level of benefit-cost ratio as the land barrier, but for roughly half the cost of the land barrier.

5.4.3. Adaptation pathways of the current development scenario

In the same manner as the previous section, the effectiveness regions for the current development scenario can be formed. Figure 5.19 shows the effectiveness regions for the current development scenario. In this case, the Highway I146 measure is always ineffective, and buyouts become effective from RCP1.9 onwards.

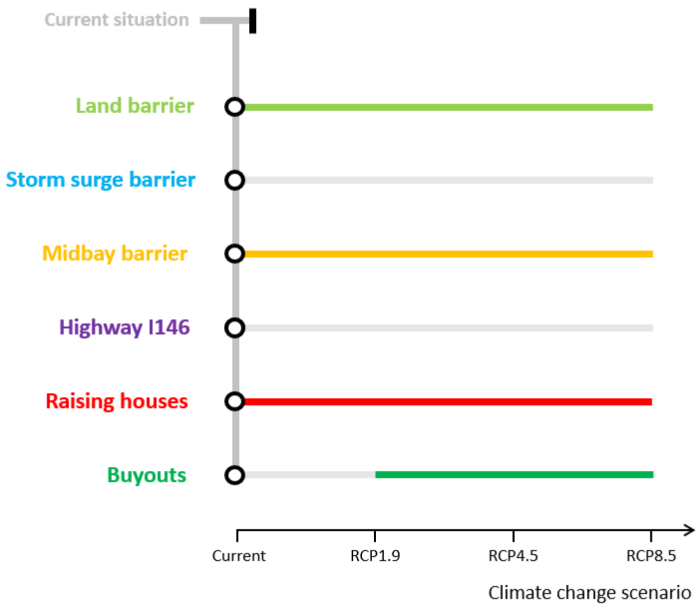
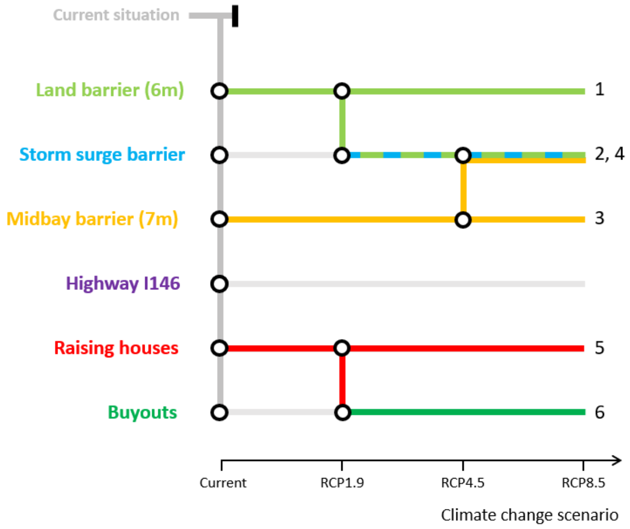


Figure 5.19: Effectiveness regions for the current development scenario

The adaptive pathways map for the current development scenario is shown in Figure 5.20. Compared to the DP1 pathways, the pathways with Highway I146 and solely buyouts are gone. Another difference is the overall lower benefit-cost ratios achieved in this development scenario due to the lower property values in the basins. The lower rate of development also translates into a lower annual safety when compared to the DP1 scenario.



Pathway		Costs Millions $	Benefit Millions $/year	Benefit/ Cost	Protected population Thousands/year
1	○	7,967	4,273	13.9	94
2	○ ○	9,259	4,857	13.2	102
3	○	3,545	2,053	14.5	60
4	○ ○ ○	12,202	4,897	10.1	106
5	○	725	167	5.8	0
6	○ ○	2,926	441	3.8	11

Table values for the RCP4.5 scenario

Figure 5.20: The adaptive pathways map and scorecard for the current development scenario

5.4.4. Adaptation pathways of the shrinkage development scenario

In the same manner as the previous sections, the effectiveness regions for the shrinkage development scenario (DP2) can be formed. Figure 5.21 shows the effectiveness regions for the current development scenario. In this case, the Highway I146 measure is always ineffective, and buyouts become effective from RCP4.5 onwards.

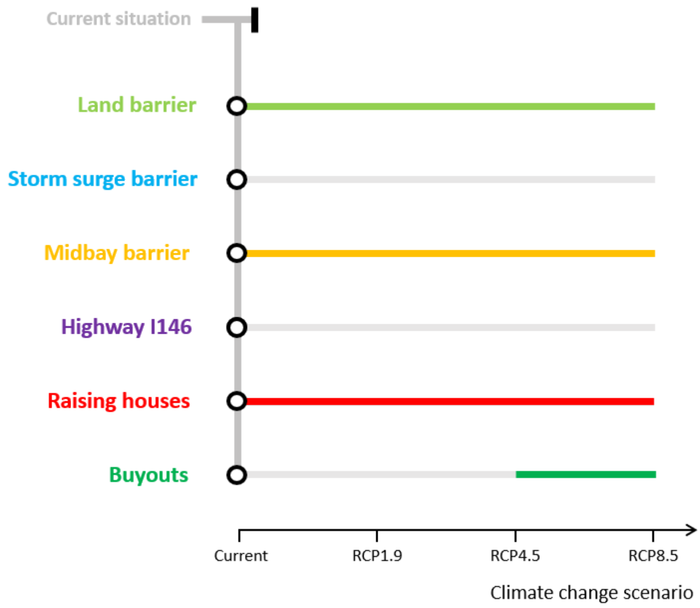
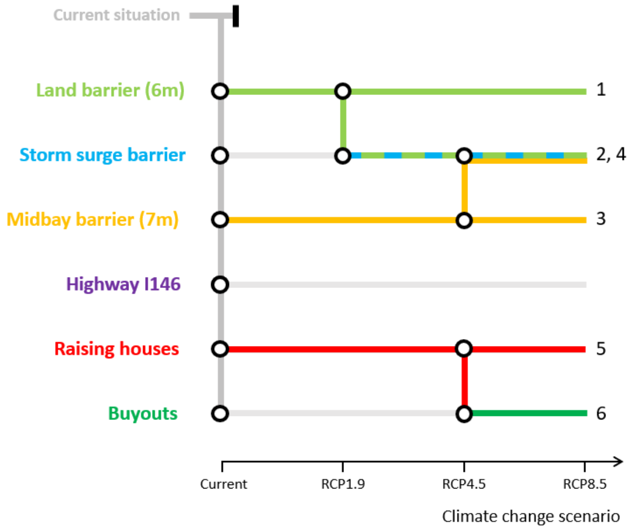


Figure 5.21: Effectiveness regions for the shrinkage development scenario (DP2)

The adaptive pathways map for the shrinkage development scenario is shown in Figure 5.22. The pathways are similar to the pathways for the current development scenario. However, buyouts only become effective somewhere between RCP4.5 and RCP8.5. The line drawn at RCP4.5 in the figure is an approximation. Compared to the current development, the benefit-cost ratios are further reduced due to the lower property values in the basins. Pathway 1, consisting of the land barrier, ranges from a 23,7 benefit-cost ratio in the growth scenario to a 9,6 ratio in the shrinkage scenario. Thus, the assumed rate of development is an important parameter of the cost-effectiveness of measures.



Pathway	Costs Millions $	Benefit Millions $/year	Benefit/ Cost	Protected population Thousands/year
1	7,967	3,055	9.6	67
2	9,259	3,400	9.2	69
3	3,545	1,437	10.5	42
4	12,202	3,428	7.1	74
5	725	117	4.0	0
6	2,926	309	2.6	7

Table values for the RCP4.5 scenario

Figure 5.22: The adaptive pathways map and scorecard for the shrinkage development scenario (DP2)

5.5. Summary and evaluation of case study results

This section summarises the most important results and conclusions of the case study.

- The land barrier is the most effective measure to reduce risk, and a 6-meter-high variant provides a risk reduction of around 75%. This also holds true for future development and climate change scenarios. However, it is also the costliest measure and requires substantial investment.
- The storm surge barrier at Bolivar Roads is only beneficial when combined with the land barrier to complete the Coastal Spine. Building the storm surge barrier on its own is not deemed cost-effective because the Bolivar Peninsula is too low and allows water to flow into the bay.
- The Midbay Barrier is the most valuable alternative to the land barrier; it requires a substantially lower investment cost but achieves a similar benefit-cost ratio. Thus, the Midbay Barrier can be a lower-cost and easier-to-construct alternative.
- Building the land barrier after the Midbay Barrier invalidates its use. However, when a benefit-cost ratio of 3 is required, the Midbay Barrier's payback period is only 7 years. Thus, if the Midbay Barrier is completed at least 7 years before the Coastal Spine, it is a worthwhile investment.
- Raising houses has a higher benefit-cost ratio than buyouts in the current climate and development scenario. However, when the climate scenario progresses to RCP4.5, they become equal. When the development scenario increases to DP1, buyouts become more cost-effective at reducing risk than raising houses. Thus, when a high rate of climate change and development is expected, it is more beneficial to start buyouts now.
- Raising houses and buyouts have limited effects due to their small scale. After a global flood risk management plan is defined, these measures are more appropriate for specific situations and small areas. The DAPP approach seems more suitable for a high-level design.
- The assumed development scenario has a significant impact on the benefit-cost proposition of measures. The benefit-cost ratio of a single measure can range from 23.7 to 9.6, depending on the development scenario.

6 Discussion

The discussion is divided into two parts. The first part, Section 6.1, considers the research methodology. Limitations to the model, simplifications, and choices made during the research process are discussed. The second part, Section 6.2, considers the validity of the results of the case study and compares the results to other research and reports.

6.1. Discussion of the method

Although the basin approach to hydraulic flood simulations offers great speed benefits over detailed 3D flood simulations provided by programs like Delft 3D, it also has some limitations. Water levels are averaged over an entire basin, and the flow effects inside a basin are not included in the model. This loses the ability to take a granular approach to implementing measures. When measures are applied to basins, they can only be directed based on elevation, not location.

Only a single depth-damage curve for all property categories has been used in the final analysis of this study. This depth-damage curve is based on residential structures of one to two floors and developed by the USACE Galveston District. No separate damage curves were used for industry or commercial properties, which can differ somewhat from the residential curve. Furthermore, data on petroleum and chemical plants was not publicly available and has been estimated based on a single data point. Also, no estimate has been made of the effect of plant shut-offs on lost revenue. Due to these effects, the reliability of the calculated damages to industrial properties is lower than the reliability of the computed damages to residential properties.

A lifespan of 40 years is used to calculate the Net Present Value for all structures. Some measures, such as storm surge barriers, might have a design lifespan of 200 years. However, these structures might fail to reach their technical lifespan due to external changes. For example, the Maeslantbarrier is slated to be replaced by 2070, only 73 years after completion, due to the effects of the accelerated rise of the sea level. A lifespan of 40 years is chosen as a conservative estimate for all measures, as a shorter lifespan limits the net present benefits and thus affects the benefit-cost ratio negatively. Therefore, the actual payback period for these measures could be shorter than calculated at the prices used in this thesis.

FEMA requires the living area of new houses to be built above the one-hundred-year flood level. Due to regulations and insurance requirements, many houses along the Gulf Coast and the Galveston Bay area have already been built at this elevation. However, existing raised houses are not considered in this study due to a lack of data on which houses have already been raised. This will cause an overestimation of the damages in these areas in the model compared to the actual situation. As a result, the measure for raising houses raises all the buildings in a basin with a set elevation, including already raised homes. Thus, the costs of raising houses in the model are also overestimated.

Furthermore, the runtime of the FLORES model is still too high. Ideally, the few discrete scenarios are modelled as a continuous range from which the EMA workbench samples. This provides more granularity in the results and helps pinpoint when measures become effective/ineffective. Furthermore, the height of structural measures can also be set to a range. This would help to find the ideal height of structural measures for a scenario or show at what height a structural measure becomes ineffective. To enable this, the runtime must be reduced. Currently, the runtime of one screening (creating a single risk curve for one set of measures and one future scenario) is around 90 to 120 seconds. In my opinion, this would have to come down to several seconds to enable a more granular analysis. It is likely possible to make some improvements in Python, as the current version of the FLORES model is still in the early stages of development. One of the advantages of Python is that it is easy to understand language and scripts. However, it is relatively slow to execute. If the model were translated to C, it could be 10 to 100 times faster.

In this study, the practical feasibility of all measures is purely judged from a technical perspective. Costs and benefits are expressed in dollars or the protection of the population. Political will and the opinion of the local population are left outside of the scope. However, these factors will become significant when a protection design must be chosen in a real case. For example, locals are often vehemently opposed to buyouts, as they are unwilling to leave their homes and communities. Social justice issues have also not been considered.

Feature Scoring analysis is useful for comparing measures of similar size and potential. Measures with significantly smaller risk reduction and construction costs appear ineffective compared to the more extensive measures in the feature scoring analysis. However, these small-scale measures might be very effective in the area where they are applied. Because they are only applied to a small area, the total effect is limited, and consequently, they appear ineffective in the feature scoring analysis. This is a point of attention when performing feature scoring analysis with measures of different scales. If raising houses is applied on all low-lying basins, the analysis might shift in favour of raising houses as the total effect becomes larger.

Similarly, it has become clear that PRIM analysis is less useful when the scale of measures/policy options differs substantially. The effects of one or more alternatives on the outcomes can quickly be insignificant, reducing the analysis's value. However, it can still be used to check the rationale for the adaptive pathways and the outcomes of earlier analyses.

6.2. Discussion of the results

The baseline risk, with no climate scenario, development scenario, or measure applied, calculated by the FLORES model, is \$4,111 million. Meanwhile, the USACE projects a risk of \$2,126 million in their Coastal Texas Feasibility study. Thus, the baseline risk is roughly twice as high as calculated by the Army Corps, which can significantly affect the results of a benefit-cost analysis. Measures are more likely to have a positive benefit-cost ratio in this study than in the Army Corps study due to the larger total risk. For the high sea level rise scenario, this difference becomes less pronounced. FLORES predicts \$7,522 million in damages under the RCP8.5 scenario, compared to \$6,108 million modelled by the Army Corps for the comparable high sea level rise scenario. One explanation for this difference is that the Galveston Ring Barrier, which is a part of the Coastal Spine plan, has not been considered in this study. This leaves Galveston City unprotected and vulnerable to flooding.

Next to the risk, the costs of measures also deviate from the costs calculated by the USACE plan. Costs of measures are estimated based on historical and comparative measures. Estimating costs in this way comes with a high degree of uncertainty, as local conditions will vary considerably, and many other factors influence a measure's final costs. Furthermore, USACE implements a wide range of measures in its Coastal Texas plan, which have not been considered in this study, such as the Galveston City Ring Barrier. Lastly, building time has not been considered in this study. Construction time and cost estimates can have a large effect on the benefit-cost ratio of measures, and more in-depth analysis is required before a decision can be made.

In some cases, FLORES will calculate a negative risk reduction when a measure is applied. This is partly due to a numerical anomaly in the hydraulic model of FLORES, which can lead to short-lived but sharp spikes in the basin water level. Although this effect only lasts a single time step in the model (6 minutes), the highest water level recorded in the basin is used for the damage calculations. The highest water level can be half or even a full meter higher due to this effect than otherwise would be the case. The higher water level drastically increases the damage in the basin and can nullify the positive effects of the measure. To negate this issue, FLORES could be altered to calculate the maximum water level elevation of, for example, the highest half-hour average.

After analysing the first screening results, upstream improvements and preventing settlements have both been removed from the final screening. Preventing settlements is essentially the same as keeping the current development scenario and was thus superfluous. On the other hand, upstream improvements suffer from a different issue, which stems from the basin approach. When the retention of a basin is increased, it does not matter where the water comes from as long as it is present in the basin. If the lowest level of the basin is close to zero due to a river or creek, inter-basin flow will be stored in the retention capacity. The basin then acts like a sink, attracting water from nearby basins. To solve this problem, a separate basin could be modelled at the exact location of the intended reservoir.

The Midbay Barrier could be significantly more effective than it is modelled in this research. After careful analysis, water appears to flow around the Midbay Barrier rather than overtop it. This flow can be prevented by building a dike between basin 13, Dickinson Bay, and basins 5, 11 and 12 along the West Bay and Texas City. If this dike is applied alongside the Midbay Barrier, the risk reduction of the measure could increase further. However, it is not expected to achieve the same level of risk reduction as the land barrier, as it does not address the flood risk on Galveston Island and Bolivar Peninsula.

This study offers several improvements over Berchum's (2017) case study of the Galveston Bay area. The current FLORES model simulates compound and inland flooding. Non-structural measures, such as buyouts, have been added and analysed. Uncertainties regarding the effects of future development and climate change have been considered. This has allowed the implementation of the Dynamic Adaptive Policy Pathways method in the study area.

7 Conclusion and recommendations

7.1. Conclusion

This research aims to support decision-making in the Galveston Bay area to develop a robust flood risk protection design. To achieve this goal, a framework was developed to analyse the flood risk for many plausible future scenarios and applied in a case study of the Galveston Bay area. Limited large-scale flood protection exists in this area, leaving large areas of land and communities insufficiently protected. The sub- and main research questions are answered on the basis of the case study.

The framework developed in this thesis consists of several steps and can be divided into two parts: the setup phase and the results analysis phase. The first step of the framework is to analyse the study area, collect necessary input data for the FLORES model and perform any required data preprocessing. The model requires elevation, storm surge, rainfall, population, development, uncertainty data, and more. The second step is to set up the model for the study area. The west coast of the bay is identified as the most risk-prone area, and flood protection or mitigation measures are derived from the USACE proposed plan and the Galveston Bay Park Plan. The third step of the framework is to verify the results of the hydraulic modelling and implemented measures. The model is verified for the 1 in 500-year storm, defined by the proxy storm 036 from FEMA. Model water level results were within 10% of the runs performed by the SSPEED centre for the baseline. With the Coastal Spine in place, the maximum water surface elevation deviation was 30% locally.

The full flood risk screening results are analysed in the second phase of the framework. The screening repeats the flood simulation for each combination of measures, future scenarios and hydraulic boundary conditions. The results of the screening are used in two ways. Firstly, questions from local policymakers are answered based on directed analyses of the results. Secondly, a broad analysis is performed on the entire result set to find interesting system behaviour, identify tipping points and establish effectiveness regions. Lastly, based on the analysis of the screening results, the dynamic adaptive policy pathways are constructed. Based on the pathways map, policymakers can be informed on robust measures, dead ends, and the effects of uncertainties on the system and compare strategies in different future scenarios.

I What future scenarios are plausible for the Galveston Bay area?
Scenario analysis has shown that uncertainty in the study area lies in the effects and magnitude of climate change and the area's development. The climate change uncertainty has been quantified in 4 distinct scenarios based on the Representative Concentration Pathways (RCP) adopted by the IPCC: Current, RCP1.9, RCP4.5 and RCP8.5. These represent a sea level rise of up to 1.31 meters at Galveston, as well as up to 5% higher wind velocity and 21% higher rainfall intensity. The development uncertainties have been quantified in 3 distinct scenarios: the current situation, continued growth (DP1) and shrinkage (DP2). These represent an increase in value and population in the area of 70% or a decrease of 30%, respectively.

II Can simple flood simulation models be used to model complex systems?
The flood risk simulation uses the Flood Risk Screening and Analysis (FLORES) Python tool. This tool can rapidly model complex systems and provide multiple objective optimisation of economic and safety results. Verification of the water surface elevation results shows a 10% deviation from more advanced modelling by the SSPEED centre. Thus, simple flood simulation models can be used to model complex systems with reasonable accuracy.

III What flood risk protection measures can best be applied in the future, and what would be their preferred timing?
The screening has shown that implementation of the land barrier and the storm surge barrier at Bolivar Roads is crucial to achieving the largest flood risk reduction in the Galveston Bay area. This combination alone leads to a risk reduction of $3,501 million per year and protects 72 thousand people from flooding annually in the current scenario. The upfront cost of these measures is $7,699 million. Flood risk of local inhabitants and economic value will benefit most if work on these measures is prioritized. However, if this measure is deemed too costly, the best alternative is to build the Midbay Barrier to protect the high-value and densely populated west coast of Galveston Bay. The Midbay Barrier leads to a risk reduction of $1,286 million per year and protects 34 thousand people from flooding annually in the current scenario. The upfront cost of this measure is $3,545 million. If the Midbay Barrier is constructed first, it should be in place for at least 7 years before the land and storm surge barrier is constructed to get a return on investment. Building the Midbay Barrier after the land and storm surge barrier is ineffective under all scenarios.

Other measures considered in the study tend to be of a smaller scale and less cost-efficient. The Midbay Barrier and the combination of the land barrier and storm surge barrier lead to similar benefit-cost ratios of larger than 20. Measures such as raising houses, buyouts and the Highway I146 levee have a benefit-cost ratio lower than 10.

IV How can Dynamic Adaptive Policy Pathways be applied to find effective pathways for the future?
Applying the DAPP method resulted in the creation of a pathway map with 8 possible pathways for the growth development scenario. This pathway map shows the land barrier and storm surge barrier as the most effective combination of measures to reduce flood risk and protect the local population. The second most effective pathway to reduce flood risk is the construction of the Midbay Barrier. This measure leaves more people unprotected; however, it also costs less than half as much as the combination of the land and storm surge barrier. On the other hand, the Highway I146 levee is never part of an effective pathway.

Building the land barrier is considered a robust option. It is effective in every scenario and can be expanded upon by adding the storm surge barrier to complete the primary line of defence. Similarly, the Midbay Barrier is also a robust option as it is effective on its own and can be supplemented with the land and storm surge barrier in the future. On the other hand, building the Highway I146 levee is not a robust option, as it is only effective in the current and RCP1.9 climate scenario under the growth development scenario.

Based on the above, the main research question can be answered. The main research question is:

How can Dynamic Adaptive Policy Pathways support decision-making in the Galveston Bay area?

The case study has demonstrated how the framework developed for this thesis can generate Dynamic Adaptive Policy Pathways to obtain useful information for policymakers, such as identifying effective, ineffective and robust measures and quantifying the performance of many strategies under many scenarios. The combination of the land and storm surge barrier is the most effective solution to reduce flood risk. On the other hand, the Highway I146 levee is ineffective at reducing flood risk. Furthermore, the land barrier and the Midbay Barrier have been identified as robust measures that should be implemented as soon as possible. A total of 20 possible pathways are identified and quantified for the

Galveston Bay area to account for various climate change and development scenarios.

Thus, this framework can analyse complex systems in many plausible future scenarios and make the results understandable. Creating a map of the pathways can make the various options clear to the general public, not just hydraulic engineering professionals. Additionally, by quantifying the performance of the pathways, policymakers can have a substantiated discussion of the benefits and disadvantages of the various options. The framework also helps identify robust options early in the process, allowing policymakers to act quickly and limit flood risk. In conclusion, there is great potential for future applications of DAPP, and I would encourage future researchers to utilise this framework also.

7.2. Recommendations

Following this research, several recommendations could be given to encourage further research or improve the framework and flood risk model results. These are:

- To utilise the full potential of the DAPP analysis, solutions should have a comparable impact on the system output parameters. The scale of some measures in the case study was much smaller than others, which caused them to become insignificant in comparison.
- The uncertainties have a substantial effect on the flood risk model outcomes. A better understanding of climate change and its effects will narrow down the range of plausible futures. However, the effect of human policy on climate and development should also not be underestimated.
- The hydraulic modelling of FLORES can still be improved to prevent the numerical anomaly seen in this study and provide more reliable results. This would remove the spikes in water surface elevation currently seen in the model and prevent results with a negative risk reduction.
- The damage modelling of chemical plants and refineries has room for improvement. In this research, the value of these plants is assumed to be based on a price per area obtained from one plant because most plants are not included in the appraisal districts dataset. Similar to residential properties, a depth-damage curve is applied to calculate the damages. This approach does not account for lost revenue due to plant downtime. Adding these losses would further improve the model.
- Damage calculations can be further improved with an accurate stock of raised houses in the Galveston Bay area. This was unavailable in this study, and all houses were modelled at ground level by default. In this study, the costs and effects of raising houses are both likely overestimated due to this lack of data.
- Executing code written directly in C can be 10 to 100 times faster than running Python code. Although Python code is easier to write and understand, the increased execution speed offers significant advantages. Reprogramming FLORES in C would allow many more different combinations of measures to be considered for a broader range of possible future scenarios.
- Further research on the area's development can help predict where economic value will increase. This helps to identify where flood risk will increase in the future and how measures can be targeted to achieve the greatest effect.

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A

Data preprocessing

The goal of preprocessing data is to manipulate the available data into the right shape and size for the model. For the FLORES model a .csv file is required with the population, elevation and development value per category listed for every contour of every basin. Furthermore, the basins and contours themselves have to been found.
The data preprocessing workflow used for this thesis is described in detail in this appendix. The process has been divided into four parts:

1. Construction of the drainage basins
2. Construction of the contours within the basins
3. Adding population data to the contours
4. Adding land parcel data to the contours

The entire workflow has been executed using QGIS version 3.22.3-Białowieża. For this example only three watersheds on the east side of Galveston Bay were analysed, however the process is the same for other areas. The last section contains a table with the exact steps and commands as performed in this appendix.

Table A.1: Data sets used for the preprocessing

Data set	Description	Source
Digital Elevation Model (DEM)	Raster data set with 0.5 meter horizontal resolution, 10 cm vertical accuracy.	Texas Natural Resources Information System (TNRIS)
Land parcels	Property and land value on a parcel basis. Location set to centroid of the parcel.	County Appraisal Districts (accessed through TNRIS)
2022 TIGER/Line Shapefiles	Population statistics on a block level.	U.S. Census Bureau

Constructing the drainage basins

The process starts by defining the drainage basins. For this research the publicly available LIDAR data provided from TNRIS was used. The first step is to merge the LIDAR data, as this is provided in many small elements. To prevent working with extremely large file sizes and unnecessary detail we then lower the resolution of the raster data to 10 x 10 meters. This results in the base DEM for the entire region. The next step is to use this DEM to build the watersheds. GRASS GIS provides an algorithm to calculate these watersheds. Thankfully this can be executed from within QGIS processing toolbox, which prevents the need to switch programs. When using the r.watersheds algorithm it is important to consider the threshold for the minimum amount of cells carefully. By increasing this threshold less watersheds can be found, which potentially miss characterizes you system. However when the threshold is set to low, very small basins with strange boundaries may form. This can be the result of noise in the DEM.

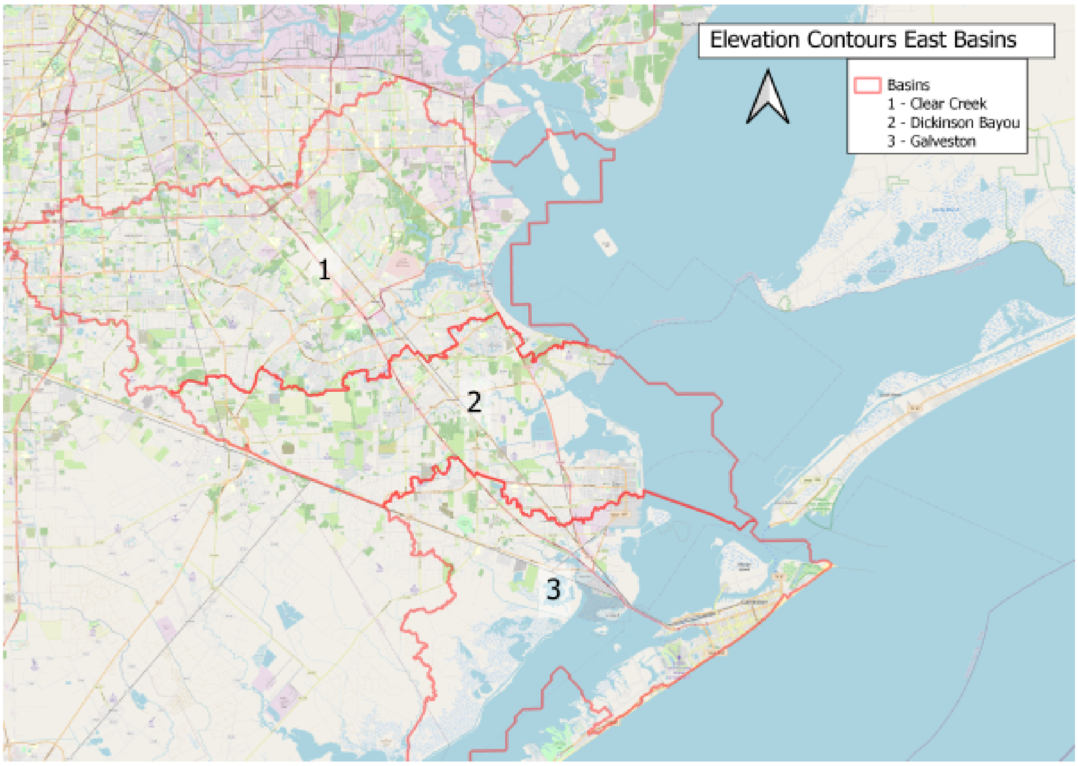


Figure A.1: The three eastern basins found along the Galveston Bay

Now that we have found the watersheds as rasters, they should be transformed to vectors as this is more use full for the rest of the process. Then the basins should be cleaned as some extremely small basins can be created in the watershed algorithm. We are not interested in these and we will merge them with the larger watersheds. Lastly the visualisation can be changed by removing the fill colour and setting the stroke colour to red to increase the visibility. The result of this first part of the process can be seen in figure A.1.

Constructing the contours within the basins

The second part of the process is to define the contours of equal elevation within each basin. The units of the DEM are meters, and we want contours of 0.25 meters. Thus the first step is to multiply the DEM by four and remove the values lower or equal to 0 to remove the water covered areas. In the second step the raster DEM is polygonized to create the polygons for the vector layer. Again the vector layer is cleaned because a lot of extremely small areas were created, which increases the computation time for the next steps. Next the contours are combined with the basins to separate the contours covering multiple basins. Then the contours can be aggregated per basin. This results in the final contour map, which is used to attribute all the population and land use data to. As a last step some fields with the minimum height, maximum height, average height and area are then added to the aggregated file.

Adding population data

The third part of the process is the addition of the population data. This data is available from the US Census Bureau on a block-by-block level. After importing the data into QGIS the first step is to clip the layer to the area of interest to remove unwanted information and increase performance. Unnecessary columns can also be removed to speed up processing. Also in this case the coordinate reference system of the population data was different from the project CRS and the data had to be re-projected first. Next step is to transform the absolute population numbers to density by dividing the number of residents per block by the area of the block.

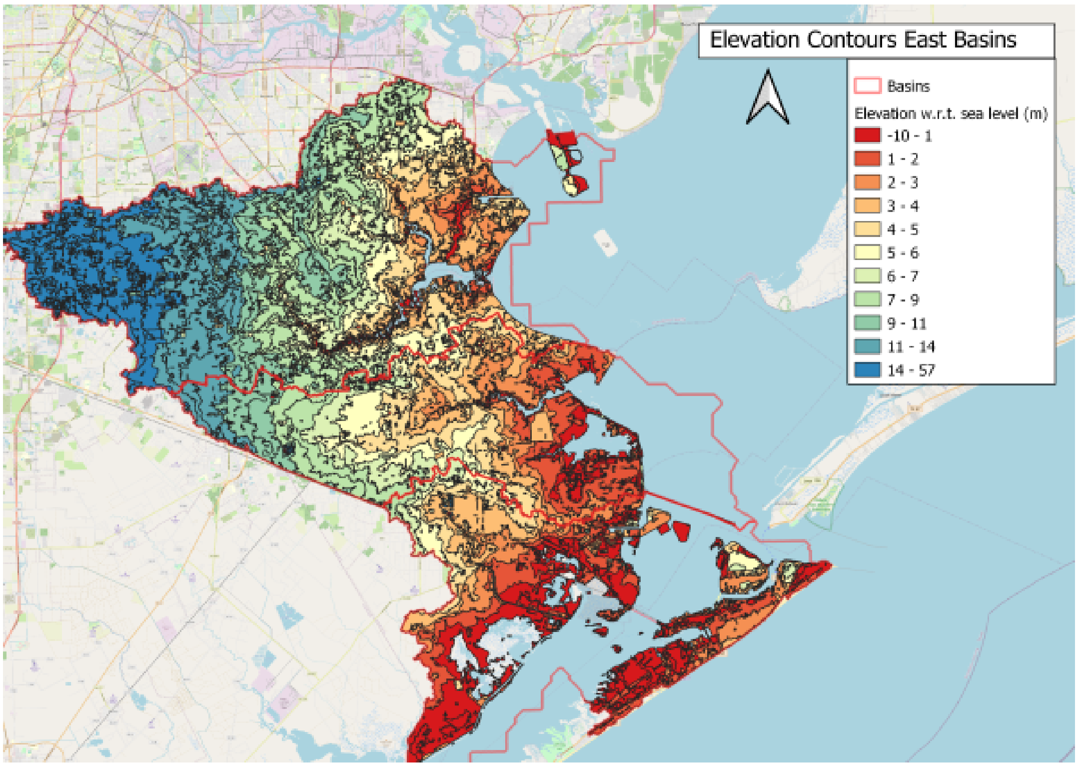


Figure A.2: Contours by height for the eastern basins

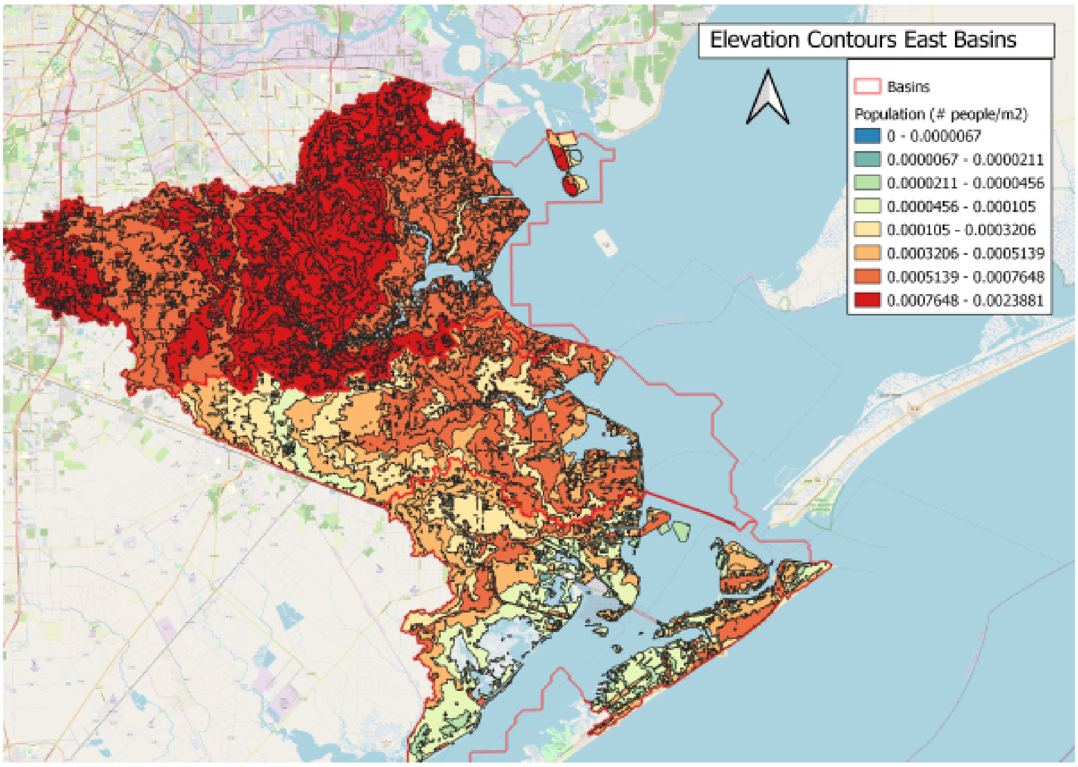


Figure A.3: Population density per contour for the eastern basins

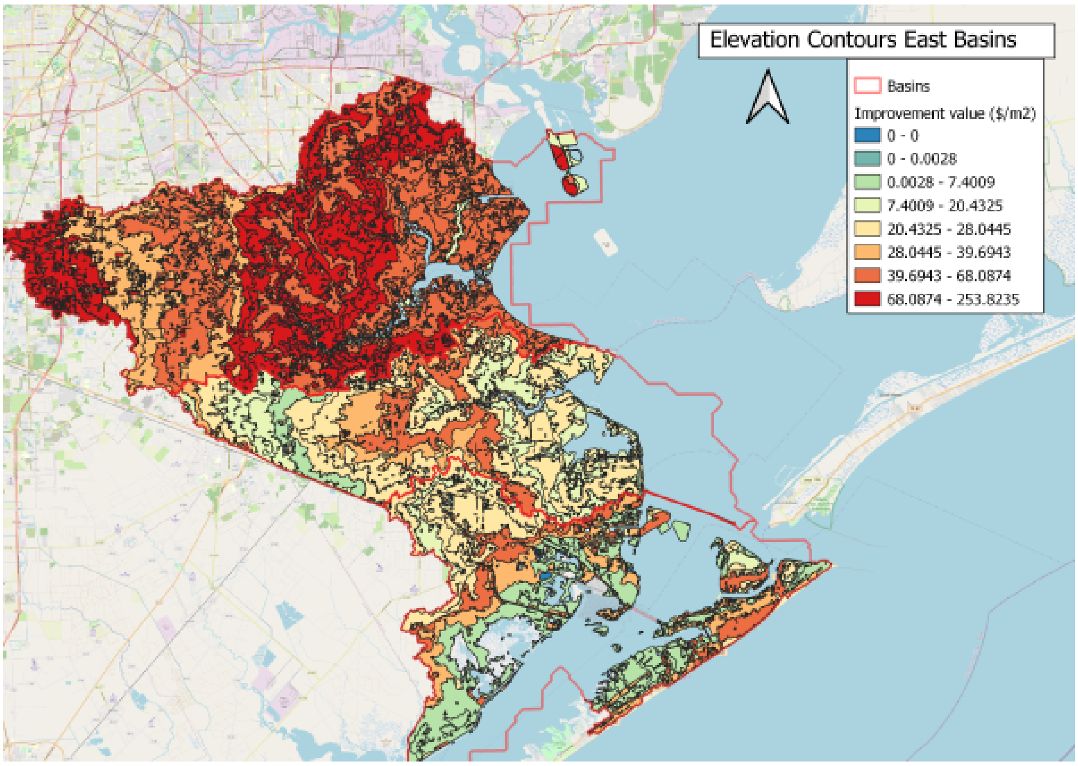


Figure A.4: Improvement value density per contour for the eastern basins

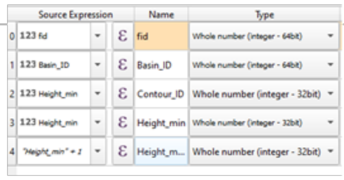
Adding land parcel data

Land parcel data is added as the last step of the process. The land parcel data is provided by the local appraisal districts of Galveston, Brazoria, Harris and Chambers counties and downloadable from the TNRIS website. This is provided in a separate shape-file per county, has to be merged. The first step is to check for any errors in the provided geometry and fix geometries where necessary. Secondly it is advised to clip the data using the basins to remove unwanted information as soon as possible. After this the data can be merged into a single vector layer and re-projected to the right projection. We can further simplify the data set, and reduce computation time as well as file size, by removing unwanted columns from the data set.

Lastly we still have to find the value per contour. This is done by first converting the parcel polygons to single points with the same attributes. Then QGIS can join the summary of these properties by location, which gives the total improvement value per contour. By adding this to the already constructed aggregate with population we obtain the total aggregated, which can be used by the FLORES model.

QGIS steps

Constructing drainage basins using DEM			
#	Step	Algorithm	Parameters
1	Download data		
2	Import DEM into QGIS		
3	Merge into one layer	gdal:merge	Select all layers
4	Lower resolution - this improves performance	Export>Save feature as...	Resolution horizontal 10m, Resolution vertical 10 m, Compression high
5	Divide area into watersheds	grass7:r.watershed	Disable all outputs except for : 'Unique label for each watershed basin', Check: 'Beautify flat areas', Min size watershed basin: 500.000
6	Change raster file into vector file	grass7:r.to.vect	Default parameters
7	Clean basins	grass7:v.clean	Threshold: 1.000.000, feature type: area, line, point, Cleaning tool: rmarea,
8	Remove all basins which only contain water from the bay. Only do this with the contours.	select manually	
9	Change visualisation	layer styling	fill colour = transparent, stroke colour = red

Contours			
#	Step	Algorithm	Parameters
1	Multiply DEM by 4. We want contours of 0.25 meters	qgis:rastercalculator	Expression: ("DEM" >= 0) * "DEM " * 4
2	Discretize DEM to get elevation contours	gdal:polygonize	Field to create: ELEVx4
	Clean contours to prevent many extremely small pieces	grass7:v.clean	Threshold: 10.000, feature type: all, Cleaning tool: rmarea
3	Combine elevation contours with the basins	native:intersection	Overlay: basins_vector, input fields to keep: [ELEVx4, fid], overlay fields to keep: fid
4	Divide elevation by 4 again to get the correct heights.	native:refactorfields	Create ELEV, Expression: ELEVx4 / 4
5	Combine contours with the same elevation within the same basin	native:aggregate	Group by expression: array("basin_fid" , "ELEV"), fid: min, elev: [mean, name: Height_min], basin_fid: [mean, name: Basin_ID]
6	Add a field for the maximum height of each contour and contour ID	native:refactorfields	
7	Add a field for the mean height of each contour	native:zonalstatisticsfb	Raster layer: DEM, prefix: Height_, calculate: mean
8	Add a field with the total area of each contour	native:fieldcalculator	Field name: area (m2), Precision: 1, Expression: $area

	Source Expression	Name	Type
0	123 fid	fid	Whole number (integer - 64bit)
1	123 Basin_ID	Basin_ID	Whole number (integer - 64bit)
2	123 Height_min	Contour_ID	Whole number (integer - 32bit)
3	123 Height_min	Height_min	Whole number (integer - 32bit)
4	"Height_min" + 1	Height_m...	Whole number (integer - 32bit)

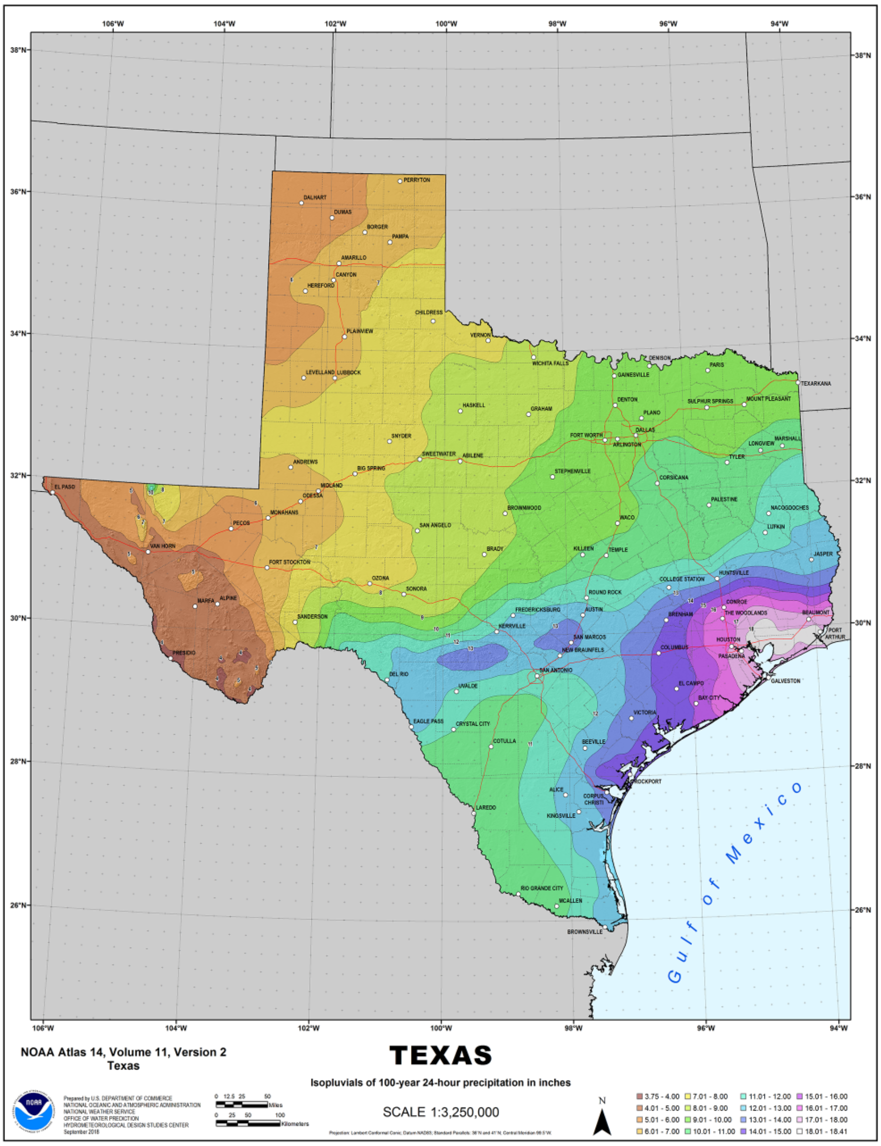
Add population data			
#	Step	Algorithm	Parameters
1	Clip layer to remove unwanted information	native:clip	
2	Add population density field to population	native:fieldcalculator	Expression: POP20 / $area
3	Reproject population data to the correct CRS, in this case EPSG 5070	native:reprojectlayer	
4	Intersect population info with aggregate	native:intersection	Overlay: aggregate, Input fields: pop_density, overlay fields: [fid, Basin_ID, Contour_ID]
5	Find total population per block section	native:fieldcalculator	Field name: population_int, Expression: "pop_density" * $area
6	Add population totals to aggregated dataset	qgis:joinbylocationsummary	join: population_intersected, geometric predicate: intersects, summarize: 'population_int', summaries: sum,

Add land parcel data			
#	Step	Algorithm	Parameters
1	Check for erros in geometry	qgis:checkvalidity	
2	Fix geometry if needed	native:fixgeometries	
3	Clip landparcel data to basins area	native:clip	
4	Merge datasets into single vector layer	native:mergevectorlayers	Destination CRS: EPSG 5070
5	Simplify dataset by removing unwanted columns		Keep fields: fid, STAT_LAND_, LOC_LAND_USE, LAND_VALUE, IMP_VALUE, MKT_VALUE, YEAR_BUILT
6a	Divide value over area	native:refactorfields	LAND_VALUE/AREA, IMP_VALUE/AREA, MKT_VALUE/AREA
7a	Intersect land parces with contour lines	native:intersection	Overlay: aggregate, input fields: [fid, loc_land_use, land_value/area, imp_value/area, mkt_value/area], overlay fields: fid
6b	ALTERNATIVE: intersection takes to long. Reduce value to a single point and check location of points in cont.	native:centroids	
7b	Add attributes to aggregate	qgis:joinbylocationsummary	Join: landparcels_eb_centroids, geometric predicate: [contains, within], fields: [.._VALUE], summaries: [sum]

B

Rainfall isopluvials

Rainfall isopluvials of the 100-year 24-hour precipitation in inches from the NOAA.



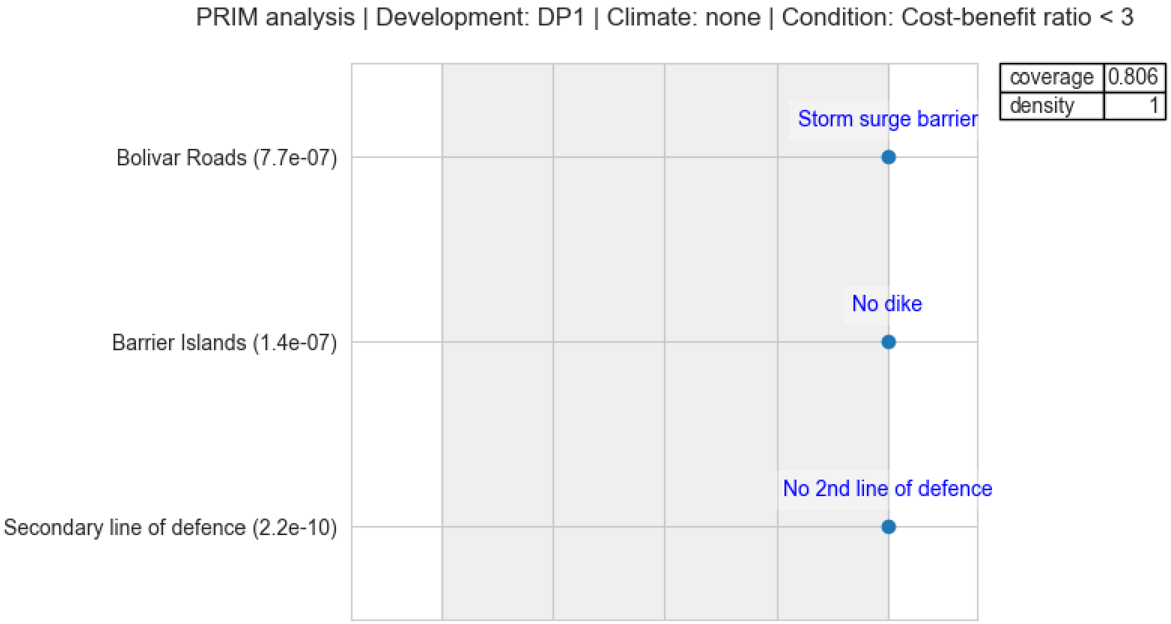
C

PRIM results

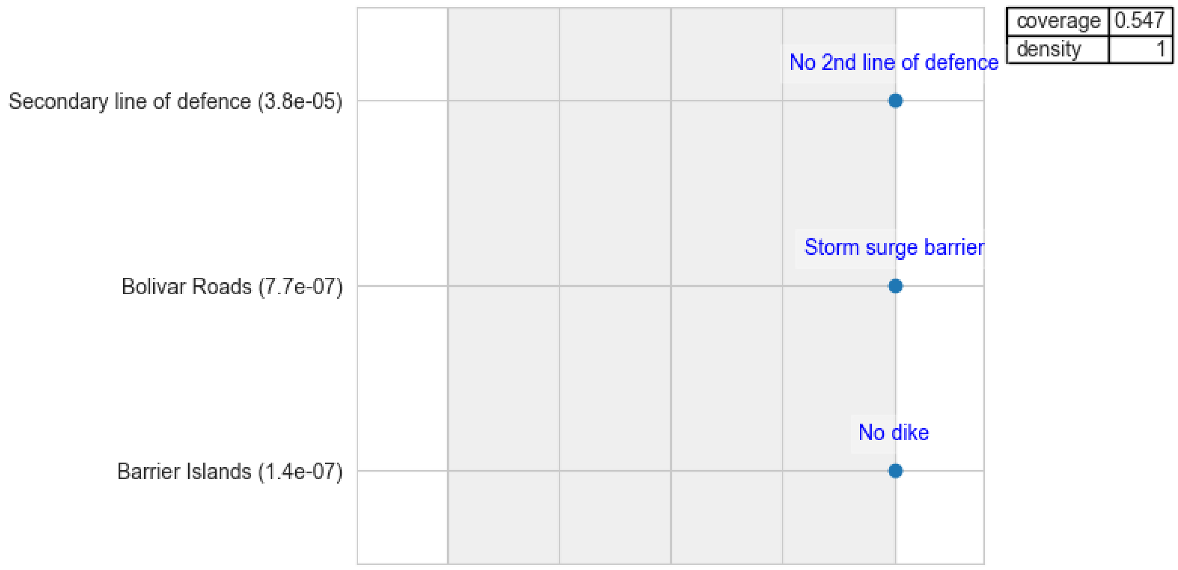
This appendix contains all the Patient Rule Induction Method (PRIM) plots required to construct the Dynamic Adaptive Policy Pathways in Chapter 5. PRIM analysis shows the values of the input parameters required to obtain the pre-specified condition of the output variable. The value right of the measure name list the quasi-p-value, or qp value. A smaller qp value indicates a larger correlation. The qp value has to be lower than 0.05 to be significant. The PRIM analysis sometimes lists measures with qp values larger than 0.05, therefore these measures are insignificant and can be neglected.

Initial PRIM analysis

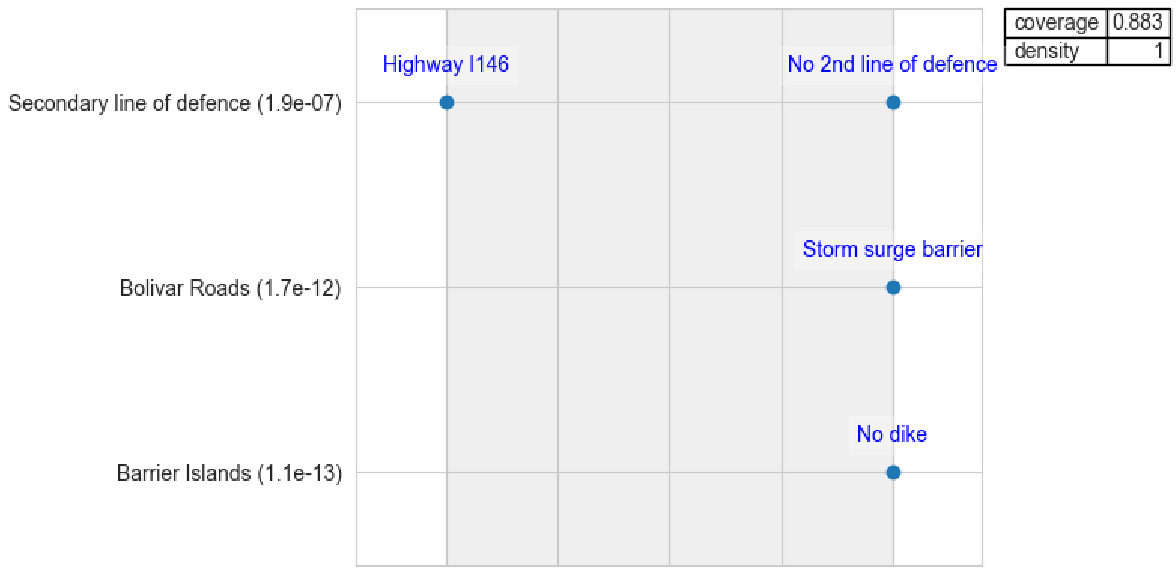
The first PRIM analysis considers all measures and scenarios. Effectiveness has been defined in the report as a cost-benefit ratio larger than 3. The first PRIM analysis performed to identify measures leading to a cost-benefit ratio smaller than 3. In this way the measures which are ineffective can be identified.

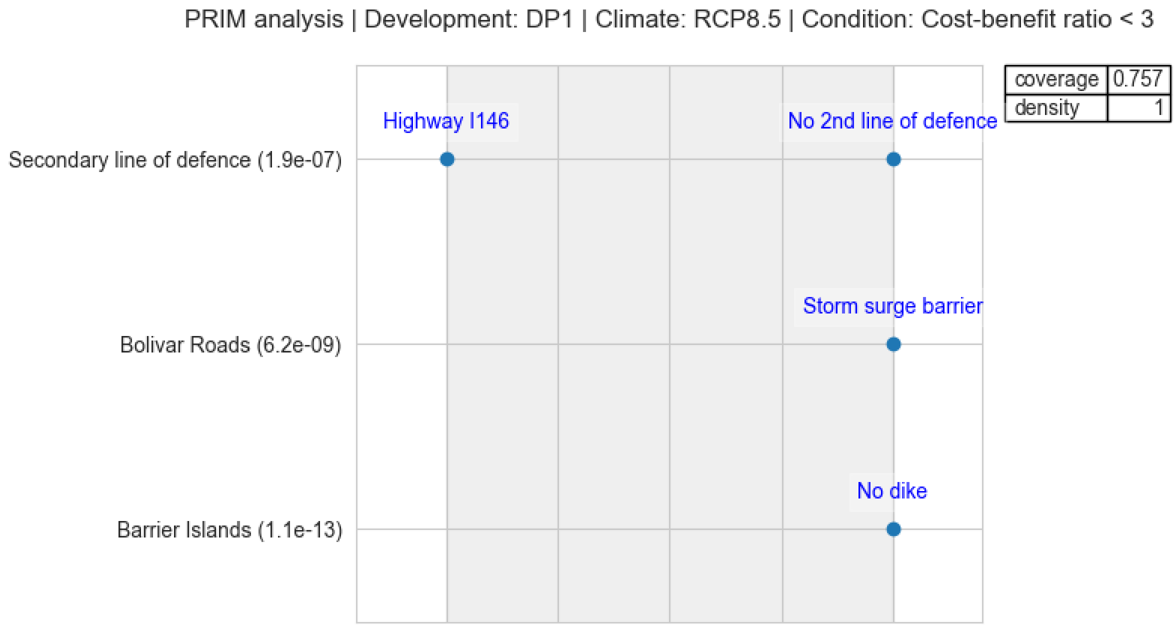


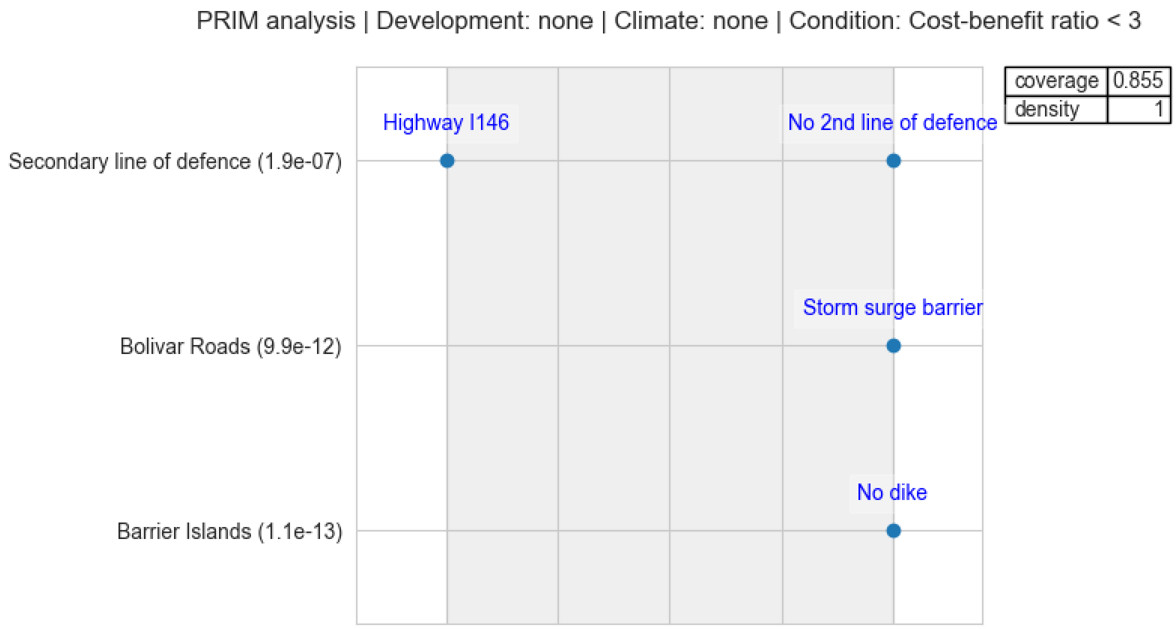
PRIM analysis | Development: DP1 | Climate: RCP1.9 | Condition: Cost-benefit ratio < 3



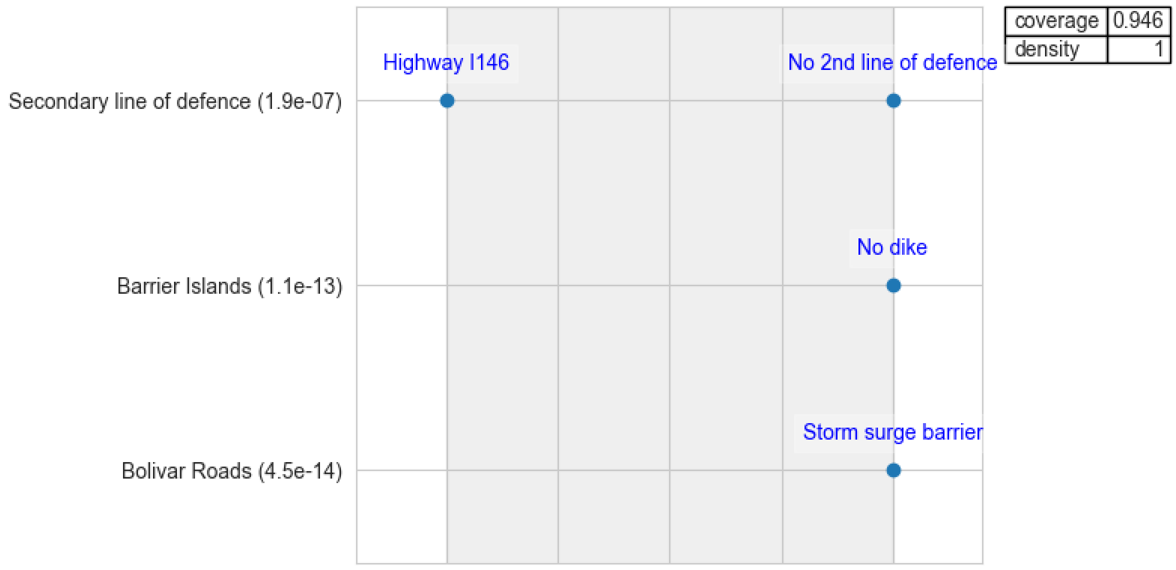
PRIM analysis | Development: DP1 | Climate: RCP4.5 | Condition: Cost-benefit ratio < 3



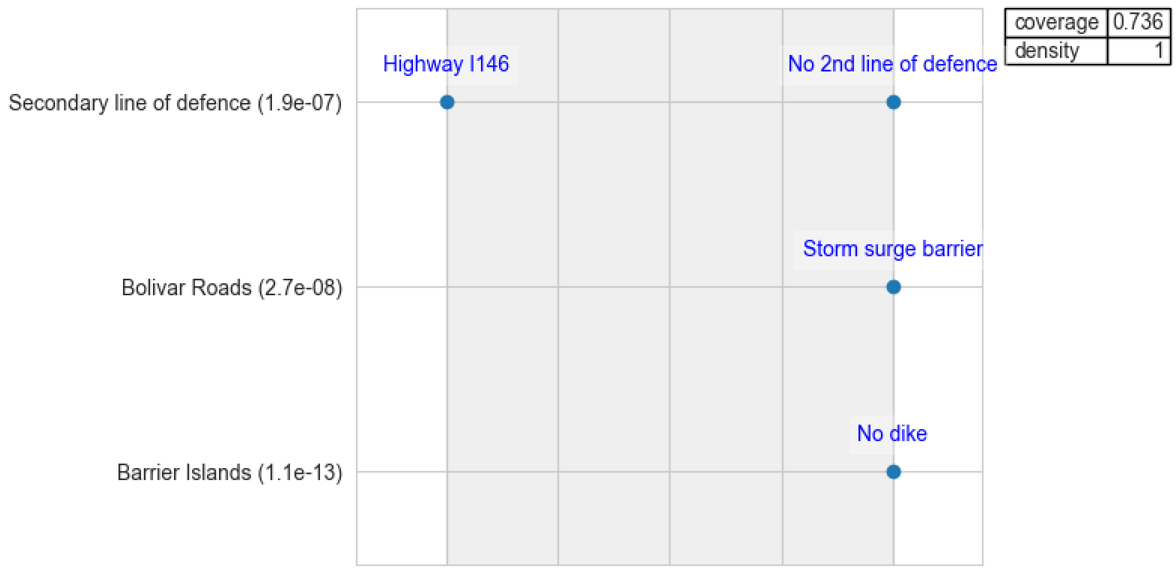

PRIM analysis | Development: DP1 | Climate: RCP8.5 | Condition: Cost-benefit ratio < 3
coverage 0.757
density 1
Secondary line of defence (1.9e-07)
Highway I146
No 2nd line of defence
Bolivar Roads (6.2e-09)
Storm surge barrier
Barrier Islands (1.1e-13)
No dike

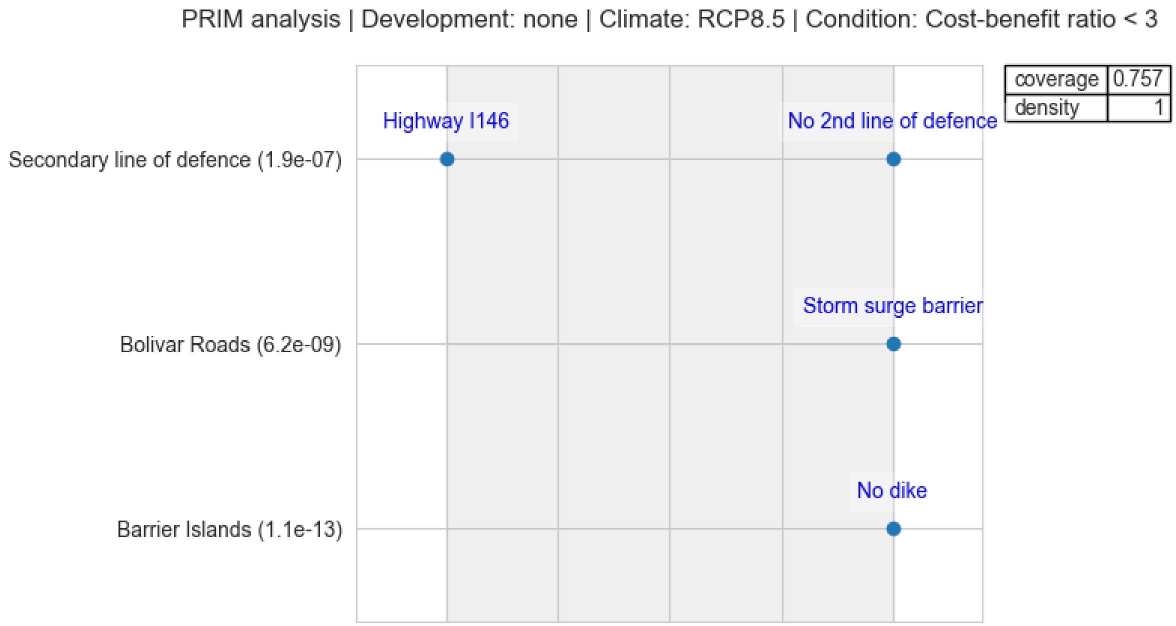

PRIM analysis | Development: none | Climate: none | Condition: Cost-benefit ratio < 3
coverage 0.855
density 1
Secondary line of defence (1.9e-07)
Highway I146
No 2nd line of defence
Bolivar Roads (9.9e-12)
Storm surge barrier
Barrier Islands (1.1e-13)
No dike

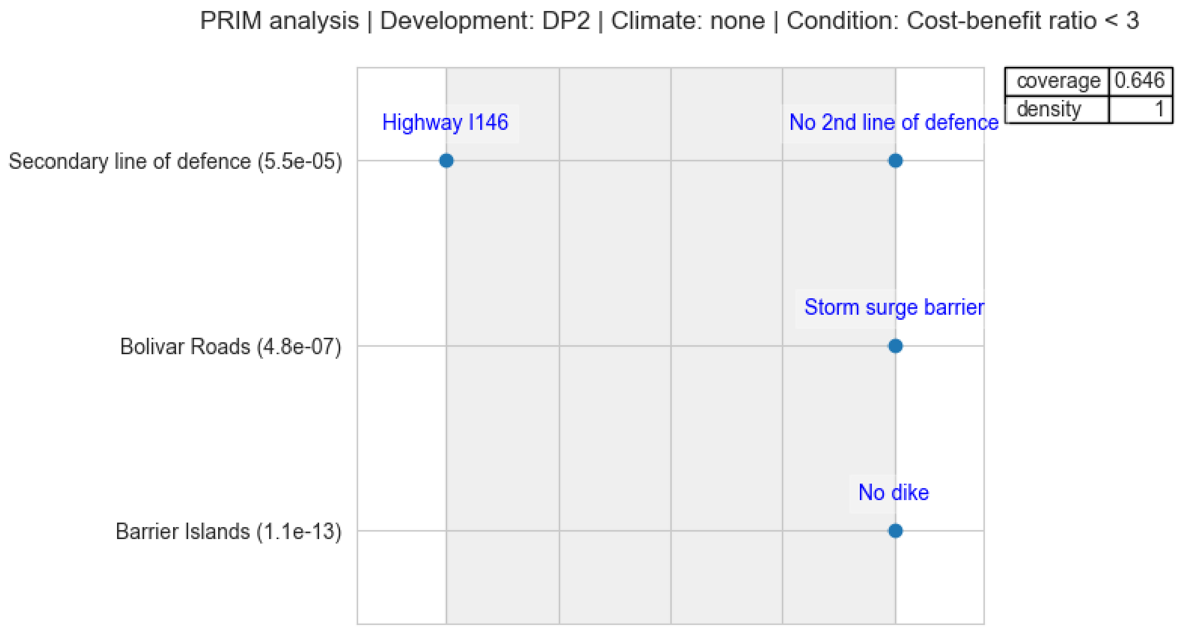
PRIM analysis | Development: none | Climate: RCP1.9 | Condition: Cost-benefit ratio < 3

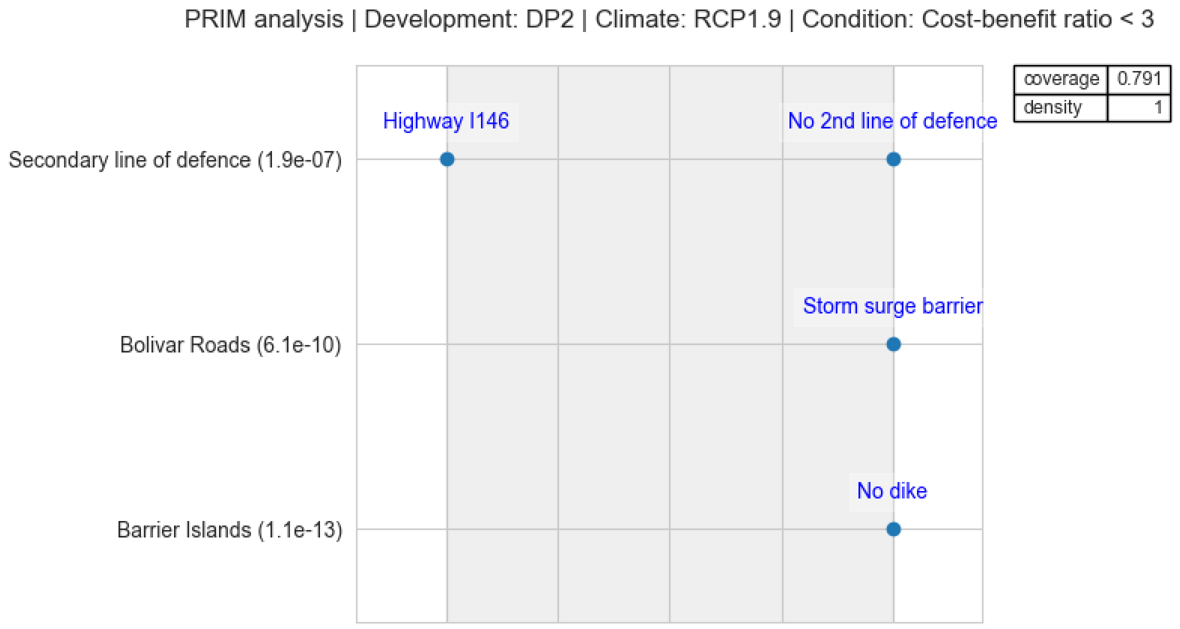


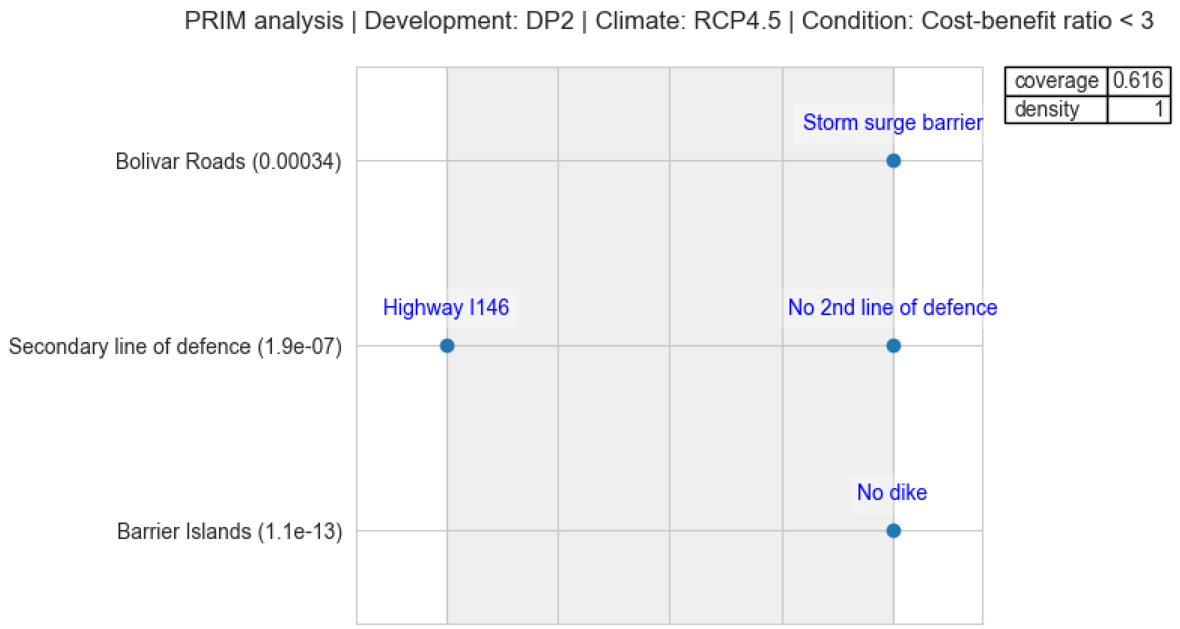
PRIM analysis | Development: none | Climate: RCP4.5 | Condition: Cost-benefit ratio < 3

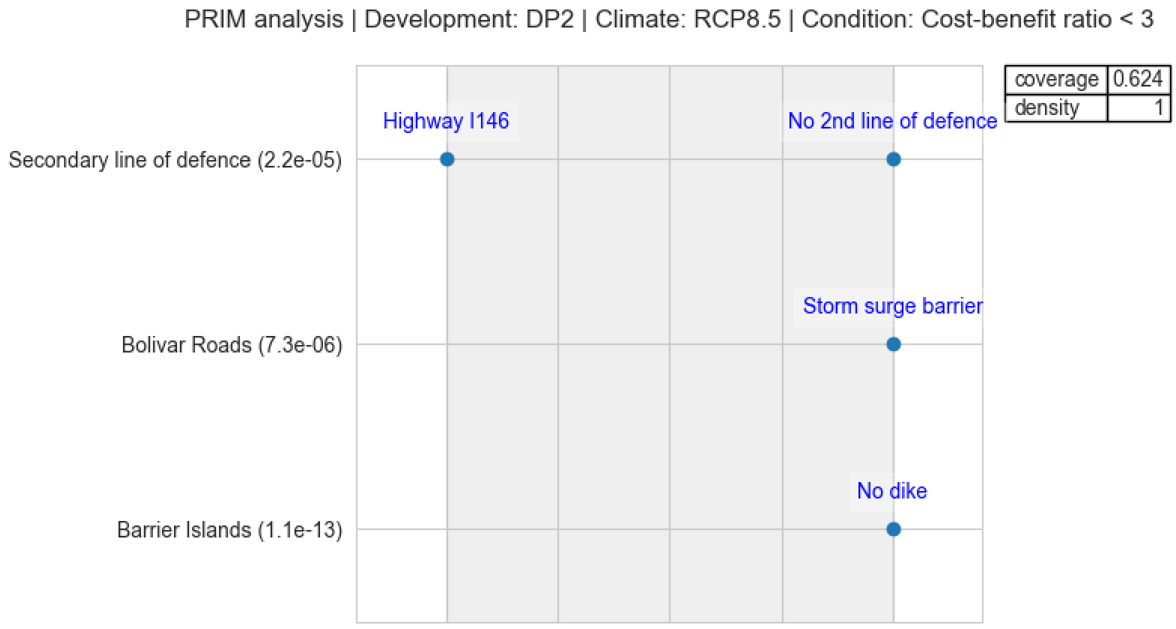



PRIM analysis | Development: none | Climate: RCP8.5 | Condition: Cost-benefit ratio < 3
coverage 0.757
density 1
Secondary line of defence (1.9e-07)
Highway I146
No 2nd line of defence
Bolivar Roads (6.2e-09)
Storm surge barrier
Barrier Islands (1.1e-13)
No dike

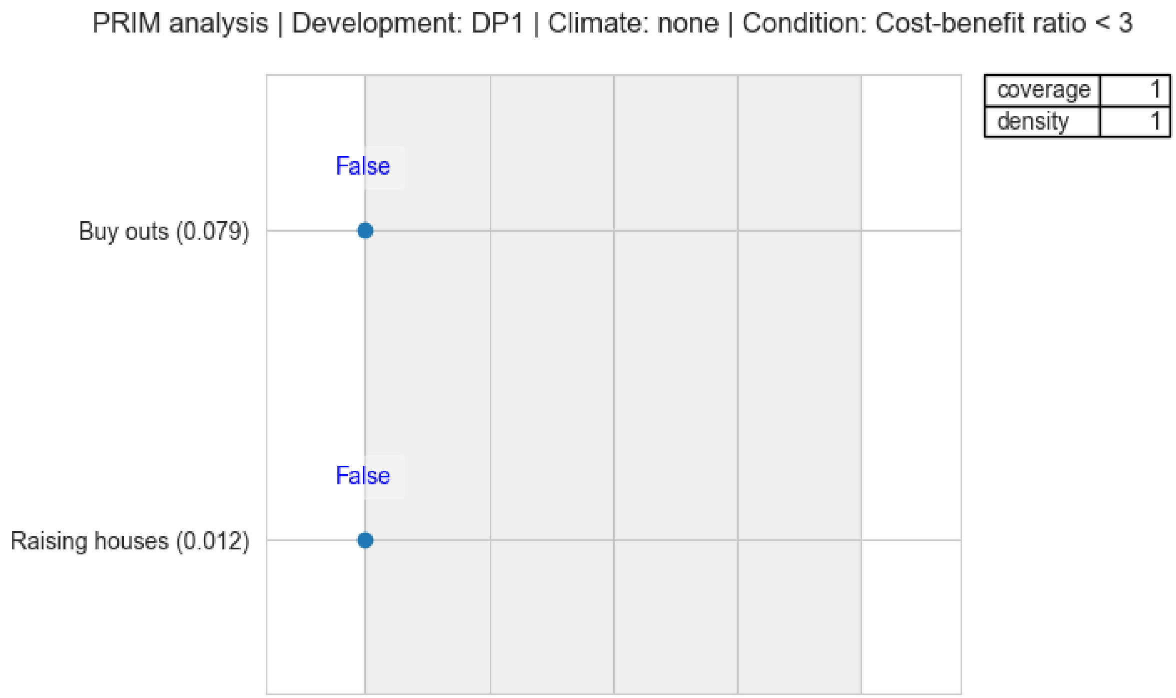

PRIM analysis | Development: DP2 | Climate: none | Condition: Cost-benefit ratio < 3
coverage 0.646
density 1
Secondary line of defence (5.5e-05)
Highway I146
No 2nd line of defence
Bolivar Roads (4.8e-07)
Storm surge barrier
Barrier Islands (1.1e-13)
No dike


PRIM analysis | Development: DP2 | Climate: RCP1.9 | Condition: Cost-benefit ratio < 3
coverage 0.791
density 1
Secondary line of defence (1.9e-07)
Highway I146
No 2nd line of defence
Bolivar Roads (6.1e-10)
Storm surge barrier
Barrier Islands (1.1e-13)
No dike

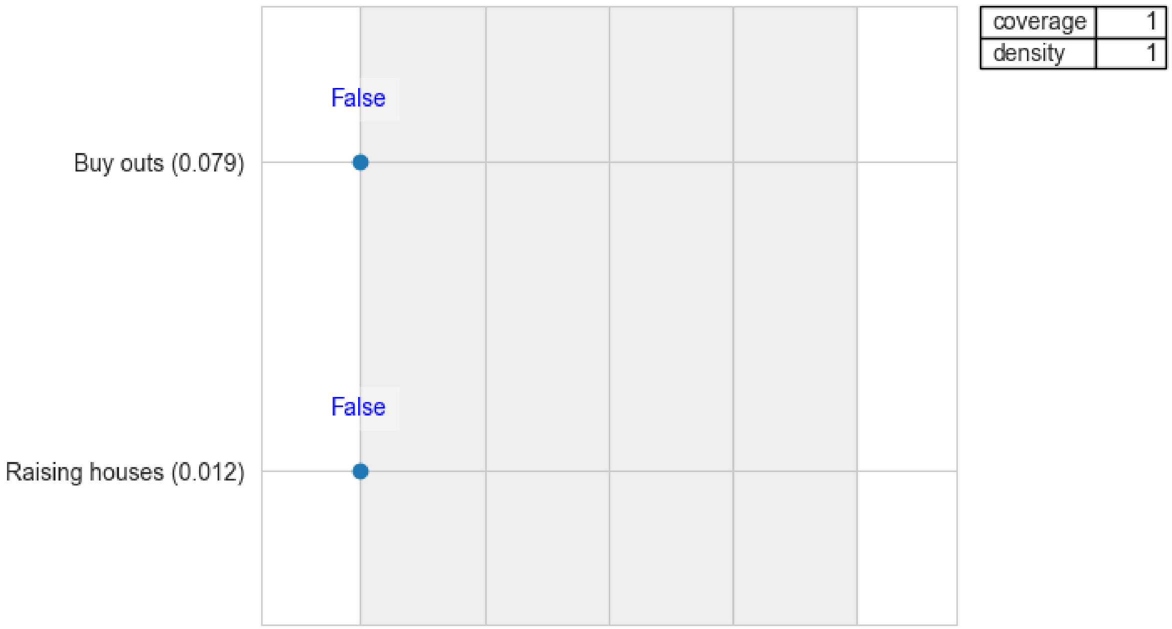

PRIM analysis | Development: DP2 | Climate: RCP4.5 | Condition: Cost-benefit ratio < 3
coverage 0.616
density 1
Bolivar Roads (0.00034)
Storm surge barrier
Secondary line of defence (1.9e-07)
Highway I146
No 2nd line of defence
Barrier Islands (1.1e-13)
No dike



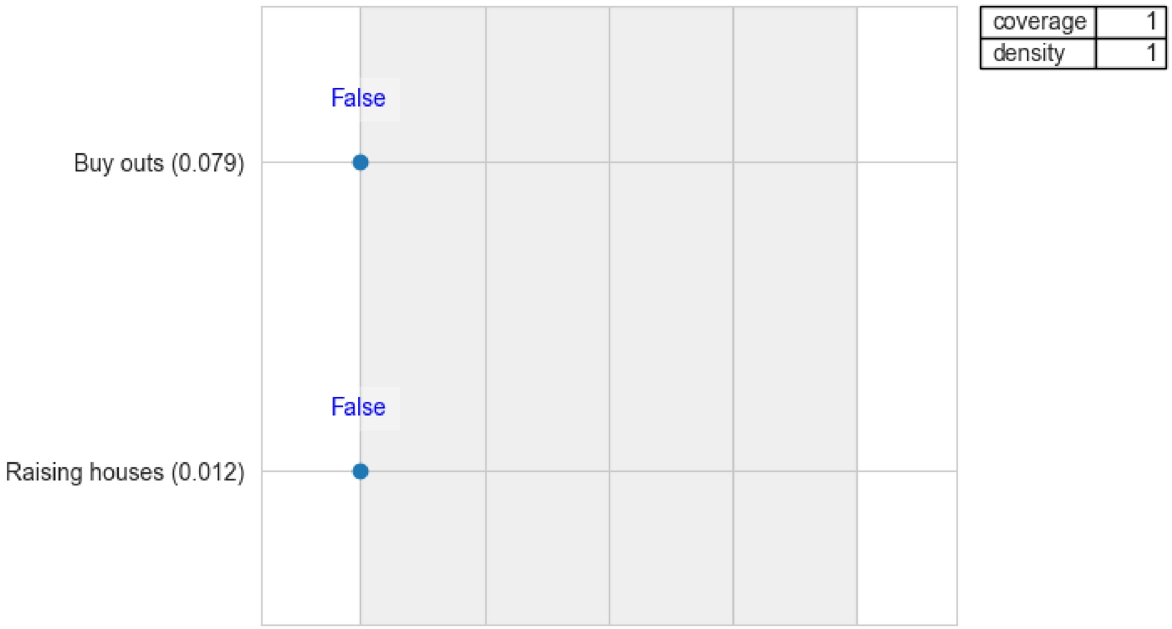
Due to the very large effect of the Ike Dike and Midbay Barrier a secondary PRIM analysis had to be performed. For this PRIM analysis all experiments containing the Ike Dike, storm surge barrier or Midbay Barrier were removed from the data set. Again the remaining measures which are ineffective, thus a cost-benefit ratio smaller than 3, were identified.

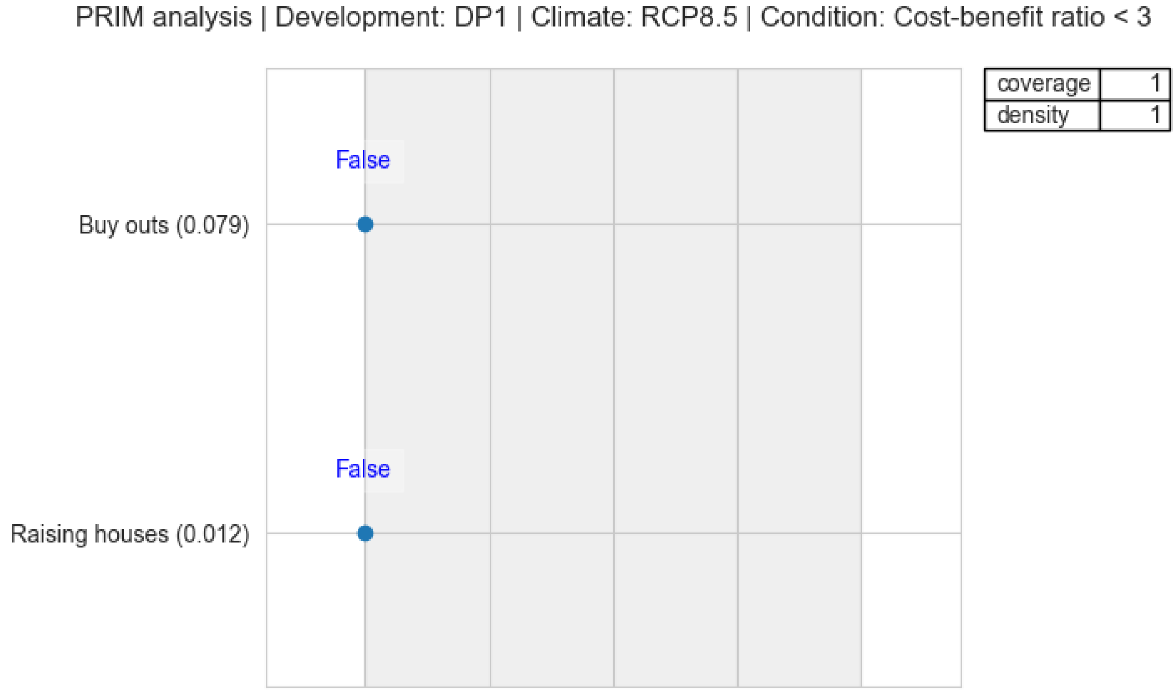


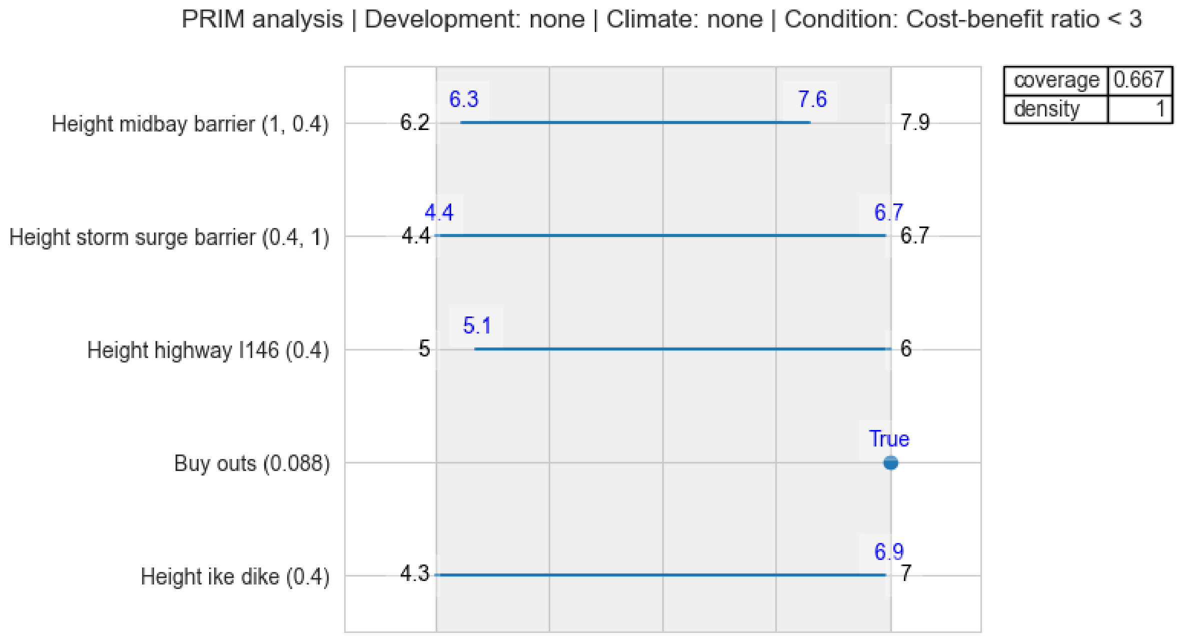
PRIM analysis | Development: DP1 | Climate: RCP1.9 | Condition: Cost-benefit ratio < 3



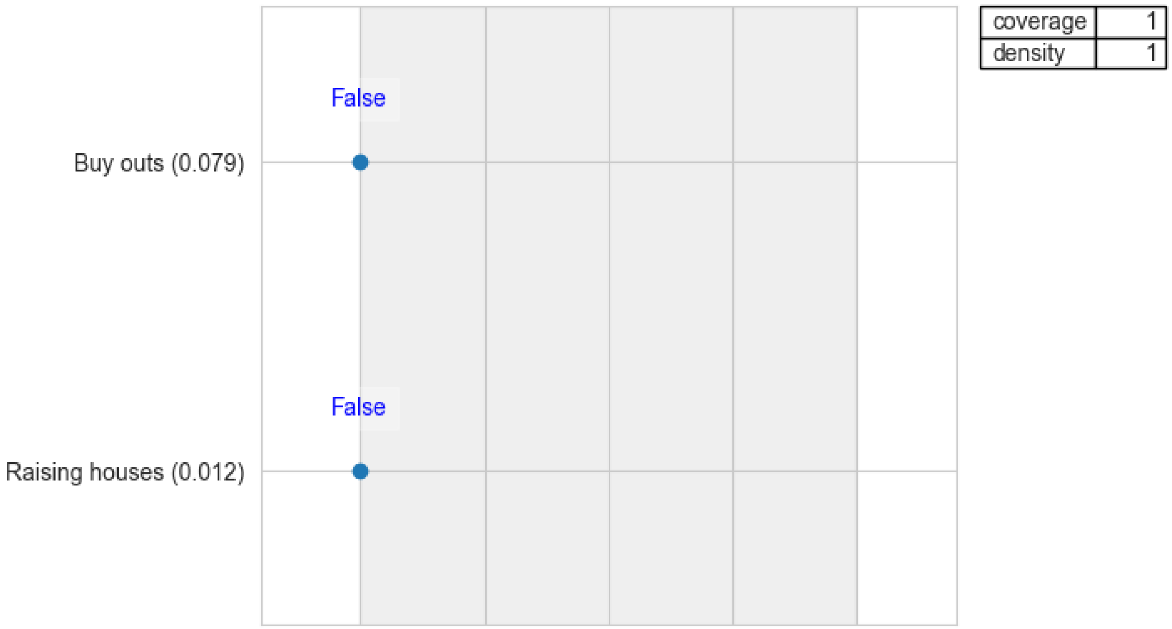
PRIM analysis | Development: DP1 | Climate: RCP4.5 | Condition: Cost-benefit ratio < 3



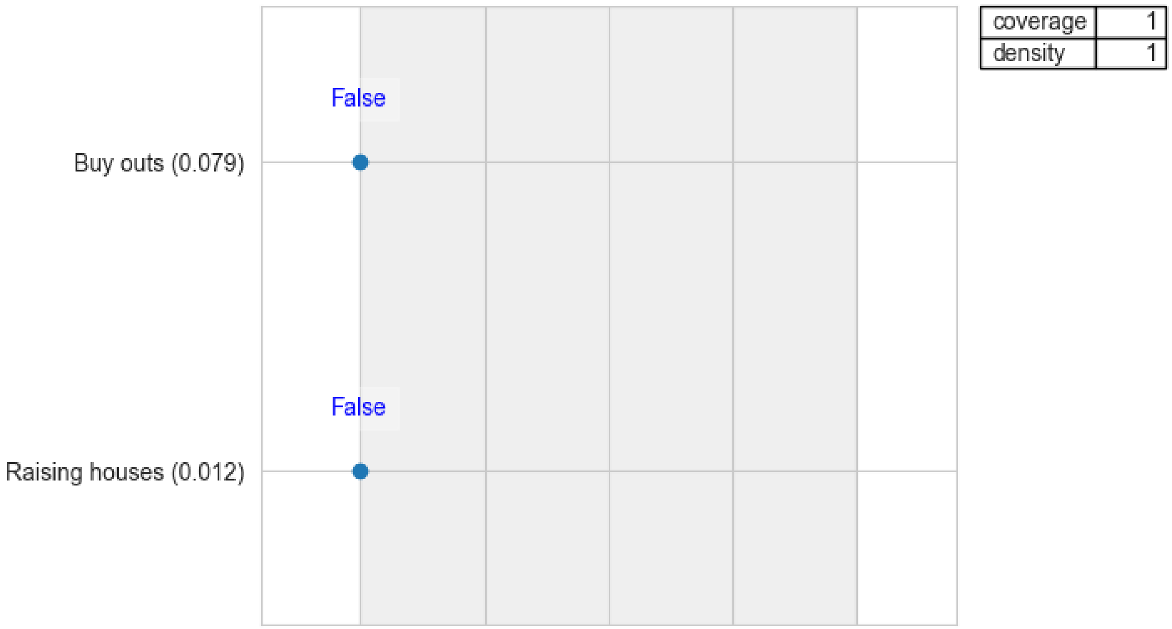

PRIM analysis | Development: DP1 | Climate: RCP8.5 | Condition: Cost-benefit ratio < 3
coverage 1
density 1
False
Buy outs (0.079)
False
Raising houses (0.012)


PRIM analysis | Development: none | Climate: none | Condition: Cost-benefit ratio < 3
coverage 0.667
density 1
Height midbay barrier (1, 0.4)
6.2
6.3
7.6
7.9
Height storm surge barrier (0.4, 1)
4.4
4.4
6.7
6.7
Height highway I146 (0.4)
5
5.1
6
Buy outs (0.088)
True
Height ike dike (0.4)
4.3
6.9
7

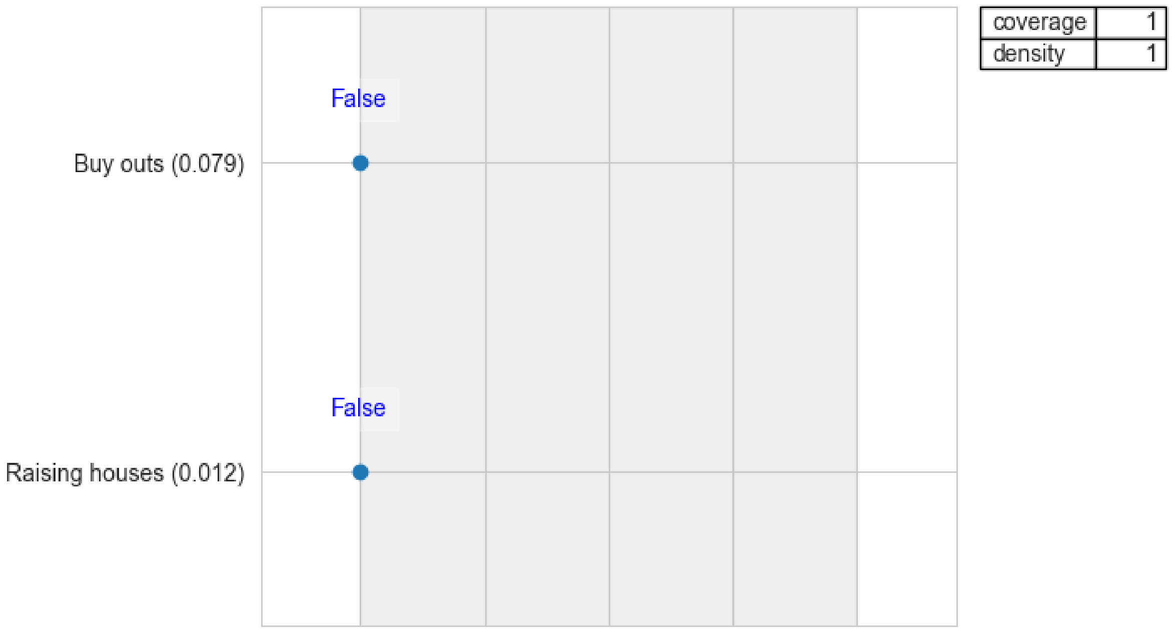
PRIM analysis | Development: none | Climate: RCP1.9 | Condition: Cost-benefit ratio < 3



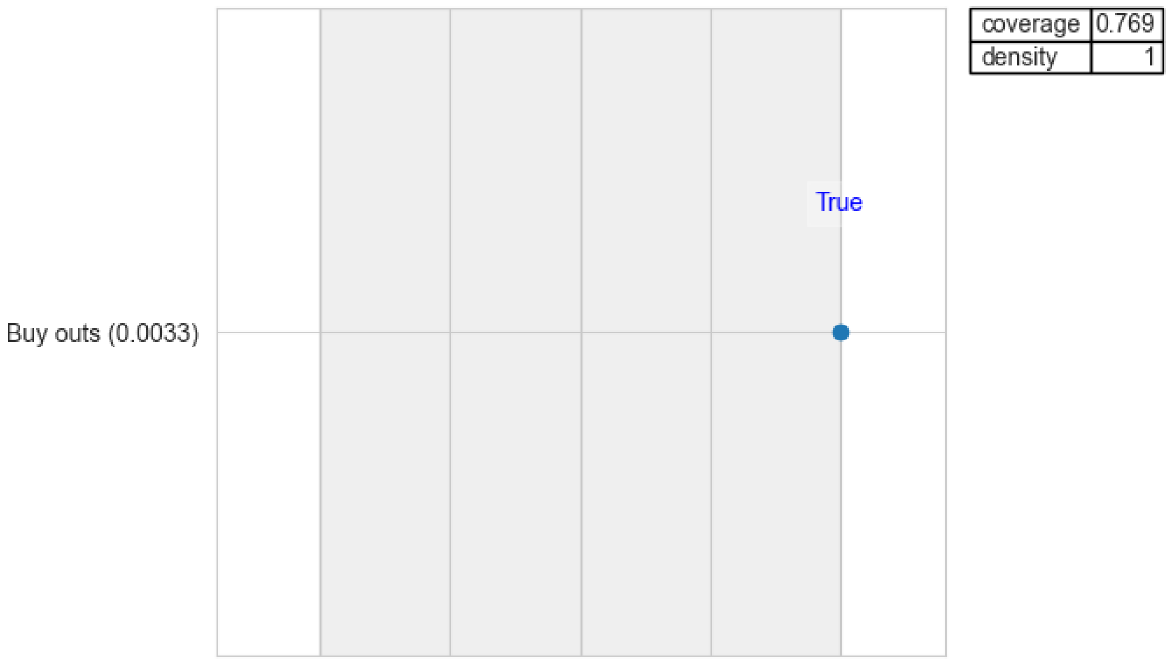
PRIM analysis | Development: none | Climate: RCP4.5 | Condition: Cost-benefit ratio < 3

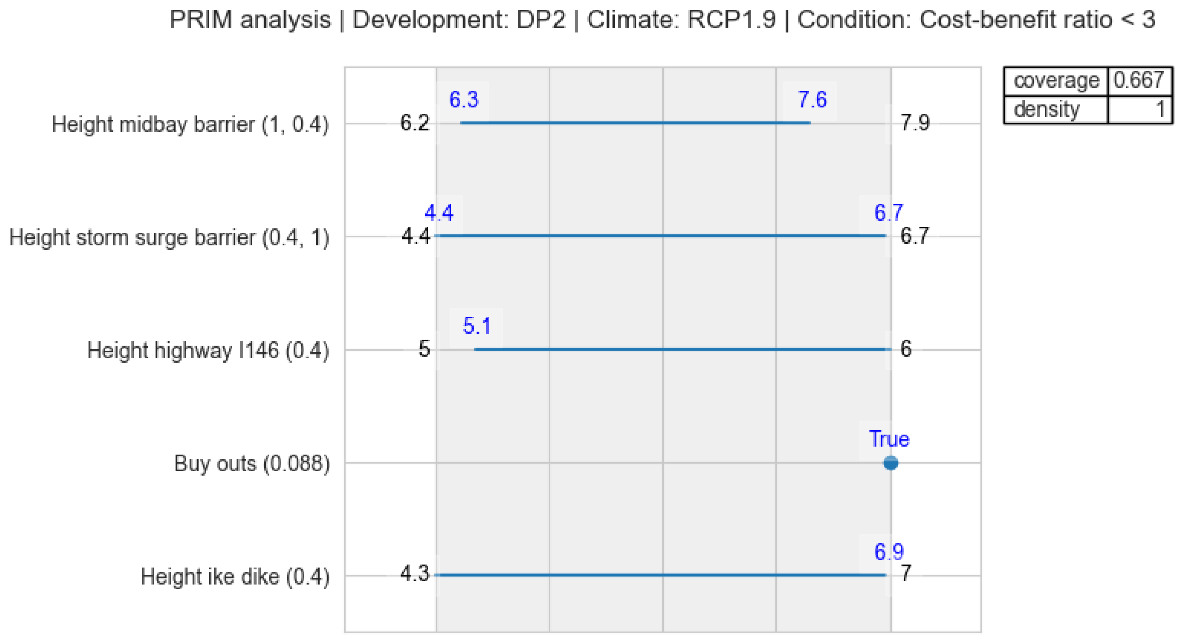


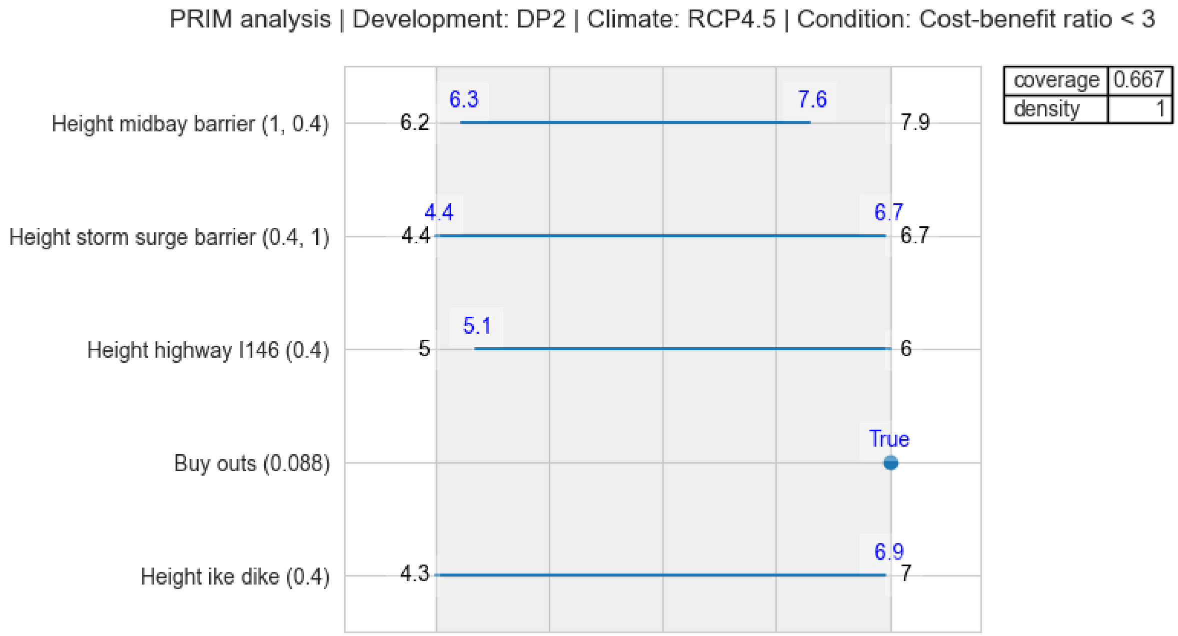
PRIM analysis | Development: none | Climate: RCP8.5 | Condition: Cost-benefit ratio < 3



PRIM analysis | Development: DP2 | Climate: none | Condition: Cost-benefit ratio < 3




PRIM analysis | Development: DP2 | Climate: RCP1.9 | Condition: Cost-benefit ratio < 3
coverage 0.667
density 1
Height midbay barrier (1, 0.4)
6.2
6.3
7.6
7.9
Height storm surge barrier (0.4, 1)
4.4
4.4
6.7
6.7
Height highway I146 (0.4)
5
5.1
6
Buy outs (0.088)
True
Height ike dike (0.4)
4.3
6.9
7


PRIM analysis | Development: DP2 | Climate: RCP4.5 | Condition: Cost-benefit ratio < 3
coverage 0.667
density 1
Height midbay barrier (1, 0.4)
6.2
6.3
7.6
7.9
Height storm surge barrier (0.4, 1)
4.4
4.4
6.7
6.7
Height highway I146 (0.4)
5
5.1
6
Buy outs (0.088)
True
Height ike dike (0.4)
4.3
6.9
7

PRIM analysis | Development: DP2 | Climate: RCP8.5 | Condition: Cost-benefit ratio < 3