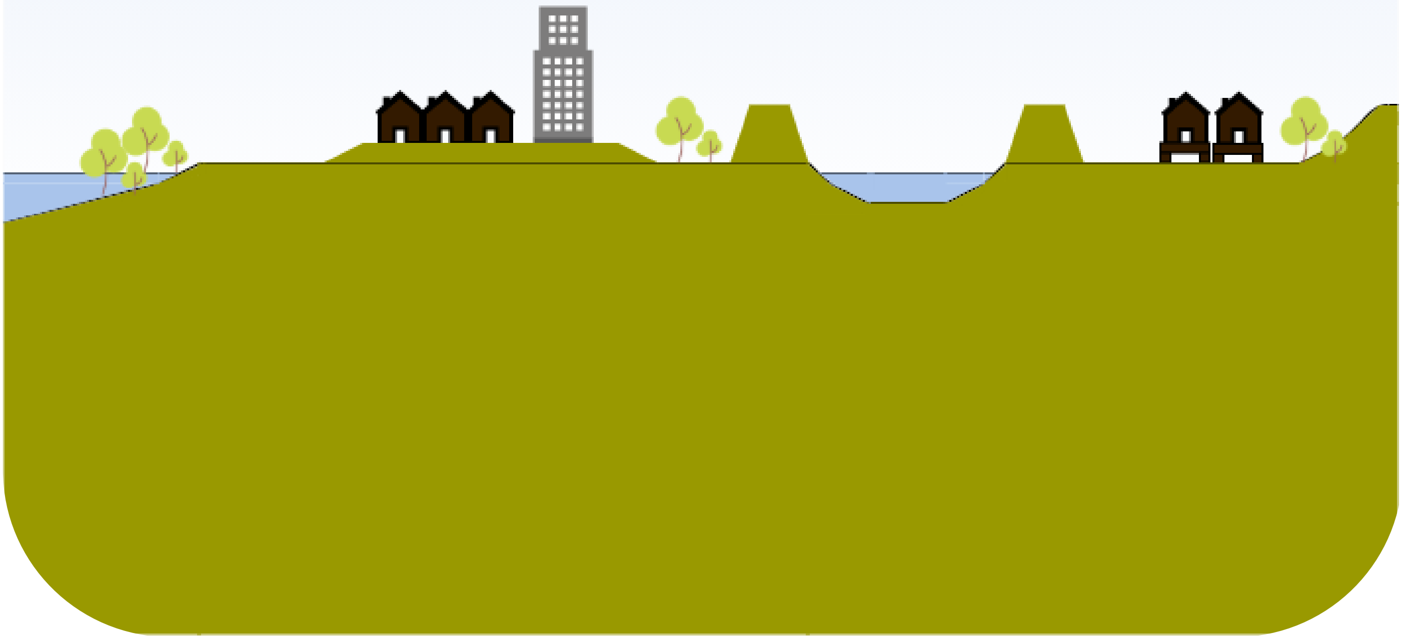
Screening flood adaptation measures framework



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April, 2021

TU Delft

Royal HaskoningDHV
Enhancing Society Together

Screening flood adaptation measures framework

by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Wednesday April 7, 2021 at 14:00.

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Project duration:	September 1, 2020 – April 7, 2021	
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Preface

You are looking at the thesis ”Screening flood adaptation measures framework”. This report is about a framework that has been developed to compare measures against flooding. The comparison looks at the costs and benefits of the measures. The report is written for my MSc thesis in Hydraulic Engineering at the Faculty of Civil Engineering, TU Delft. I have worked on this thesis from September 2020 to March 2021. The need for the framework originated at Royal HaskoningDHV, which is developing the Global Flood Risk Tool. This tool is able to map current flood risks and the intention is to further expand this application.

During my internship at Royal HaskoningDHV in 2019, I came into contact with Matthijs Bos (my daily supervisor). Eventually we came to my graduation topic together. My fascination for flood probabilities and risks in combination with programming in Python made this an excellent subject for my graduation. Analyzing the literature and developing the framework went well, with the help of my supervisors from Royal HaskoningDHV. My supervisors at TU Delft helped me to reach the academic level.

Firstly, I would like to thank Matthijs Bos for the good availability and for always being open to discuss my questions together. Despite the COVID measures, I felt like he was sitting next to me when I needed help. I want to thank Ric Huting and my other colleagues at Royal HaskoningDHV for the interesting and creative contributions. I would like to thank my supervisors at TU Delft for their clear insights and useful comments during the progress meetings. Finally, I want to thank my family and friends. You gave me the relaxation I needed during the months that I worked on my thesis, especially because there were few activities possible.

Friso Dam
Vogelenzang, March 2021

Summary

Flood risk is a way of expressing the vulnerability of areas to flooding. It contains the flood probability and the corresponding consequence. Flood adaptation measures can be taken to reduce this risk. A method is desirable for screening possible measures as an alternative to the existing analytical screening method of Royal HaskoningDHV (RHDHV), which is time-consuming. Instead of an existing method or tool, a new framework is required that fits well with the current method.

In this thesis, an answer is given to the following research question: ”How can flood adaptation measures be screened within the risk-based approach to evaluate a list of possible measures without hydraulic modelling each measure?”

A Python-based framework has been developed for this. This framework calculates the costs and benefits (reduction of the economic risk) of adaptation measures by making adjustments to inundation maps, land use and damage functions. The framework contains eleven different adaptation measures and focuses only on economic flood risks. The development started with analyzing the existing methods for comparing measures. Using the strong and missing elements of the existing methods, the functional requirements for the framework were determined. Thereafter, the functional requirements were elaborated step-by-step in the form of a Python script. To determine whether the framework is a good alternative to the existing analytical screening method of RHDHV, the framework was applied at two case locations, namely Phu Loc (Vietnam) and the Waal and Eemhaven (Rotterdam, the Netherlands). These locations have also previously been worked out with the analytical method, which allowed the results to be compared.

The analysis of the existing methods showed that transparency is an important part of the screening of measures. This involves clearly showing the various components of the costs and benefits of the measures. It was also found that the ability to adjust the measures, location and variables for the user leads to a broader applicability. A new element compared to the existing methods is an uncertainty analysis showing the bandwidth of the results, which is useful for risk calculations. After determining the functional requirements, based on the above aspects, the output of the framework consists of seven components: risk maps, damage graphs, cost graphs, a net present value box plot graph, a table with measure sizes, a table with results and background information. The measures with good results from the developed framework were generally similar to the proposed measures by RHDHV for the investigated case locations. The simulation time of the framework varied between 9 and 258 seconds, which is faster than applying the existing analytical method (order of days). Therefore, the framework is a good alternative to the analytical method of RHDHV when screening the included measures.

It has been concluded that screening of the eleven considered measures without using hydraulic simulations can be done using the developed framework. The framework is fast and uses a widely applicable method, which makes it suitable for screening. The output ensures that the simulation is transparent. Both the optimal measures and the optimal protection levels per measure can be found with the framework. The well-organized input file ensures that the variables can be easily adjusted. However, it is important to mention that not every measure is included. Therefore, the non-included measures still need to be screened with the existing RHDHV method, such as river widening. In addition, no data sets containing the spreads of investment costs were available, so that it was not possible to make a proper estimate of the standard deviations in the uncertainty analyses. It is therefore recommended to add an extensive cost database to the developed framework, from which the mean and standard deviation of measure costs can be derived. If more measures - which influence waves or currents and not directly flood depths - need to be screened with the framework than the current eleven implemented measures, it is recommended to support the framework with a hydraulic model.

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Nomenclature

The following list contains the symbols of the variables used in this report.

Symbol	Variable	Unit
A	Area	m^2
AAD	Annual averaged damage, yearly expected flood damage	€/year
ARR	Annual risk reduction, yearly avoided flood damage	€/year
BCR	Benefit-cost ratio	-
C	Marginal measure cost	€/m, €/m^2
CN	Runoff curve number	-
d	Inundation depth	m
D	Economic flood damage	€
h	Height	m
I	Investment cost	€
I_a	Initial abstraction	m
IDF	Indirect damage factor	-
IRR	Internal rate of return	%
L	Length	m
n	Number of return periods	-
N	Number of simulations	-
NPV	Net present value	€
OM	Operation and maintenance cost	€/year
P	Rainfall volume	m
P_f	Failure probability	-
PV	Present value	€
Q	Direct rainfall runoff	m
r	Discount rate	%
R	Flood risk	€
S	Potential retention	m
T	Time horizon, considered period of a cost-benefit analysis	years
T_r	Return period	years
TC	Total costs	€
α	Damage function	-
β	Risk factor	-
η	Reduction effect	-
μ	Mean of probability distribution	-
σ	Standard deviation of probability distribution	-

The following list contains explanations of the abbreviations used in this report.

Abbreviation	Meaning
1D	One-dimensional
2D	Two-dimensional
AAD	Annual averaged damage
ARR	Annual risk reduction
BCR	Benefit-cost ratio
CBA	Cost-benefit analysis
EWS	Early warning system
GFRT	Global Flood Risk Tool
GTSR	Global tide and surge reanalysis
IRR	Internal rate of return
LIR	Local individual risk
MCA	Multi criteria analysis
MLS	Multi-level safety
NPV	Net present value
PRIM	Patient Rule Induction Method
PV	Present value
RHDHV	Royal HaskoningDHV
TC	Total costs

1
Introduction

The possible dangers in flood prone areas are often expressed in flood risks. This report is about developing a framework that screens measures that reduce the flood risk. In the first chapter, the objective of this thesis is given after a general introduction of the subject. The broader context can be found in Section 1.1. In Section 1.2, the problem is defined from the subject context. The research questions and objective are given in Section 1.3. Lastly, Section 1.4 presents the overview of this report.

1.1. General context

Research proved that floods have become more severe and occur more frequently during the last century. The mean sea level as well as heavy rainfall, peak river runoff, high waves and storm surge increase globally because of climate change (IPCC, 2019). Moreover, the vulnerable areas – for instance coastal river deltas – experience urbanization. This urbanization leads to higher flood probabilities but also larger flood consequences (Konrad, 2003). In combination, these effects cause increasingly noticeable flood hazards now and in the future.

Nowadays, a commonly used term to quantify the vulnerability of areas is the flood risk. This risk can be found by the multiplication of the flood probability and the consequence. Each flood scenario has an associated risk. Usually, the risks of all considered flood events are combined to find the (yearly) expected damage or loss (see Equation (1.1)).

$$\text{Risk} = \sum_{i} \text{Probability}_i \cdot \text{Consequence}_i \tag{1.1}$$

The flood risk can be expressed in different ways. The three most important categories of flood risk are (Royal HaskoningDHV, 2020d):

- **Economic risk**
  In this risk category, the consequences of a flood are expressed in monetary terms. With this, direct damage to buildings, but also indirect damage, such as loss of income, can be determined. The emphasis is on the economic risk in this thesis.
- **Socio-economic risk**
  Socio-economic risk includes effects on people, critical infrastructure and cultural heritage. Areas depend on the critical infrastructure (e.g. hospitals, airports and power plants). Failure of this must therefore always be prevented. Individual risk and social risk are forms of the socio-economic risk. The individual risk, which is also called the local individual risk (LIR), stands for the probability of death per year for an individual person caused by a flood event. With the social risk the focus is on the number of affected people from a flood event (Jonkman et al., 2018). This can be about the people who passed away but also about people with a form of injury.

- **Environmental risk**
  This risk type relates to disturbance or destruction of (natural) habitats. If the flood causes damage to, for example, tanks, leakage may occur and pollutants are released.

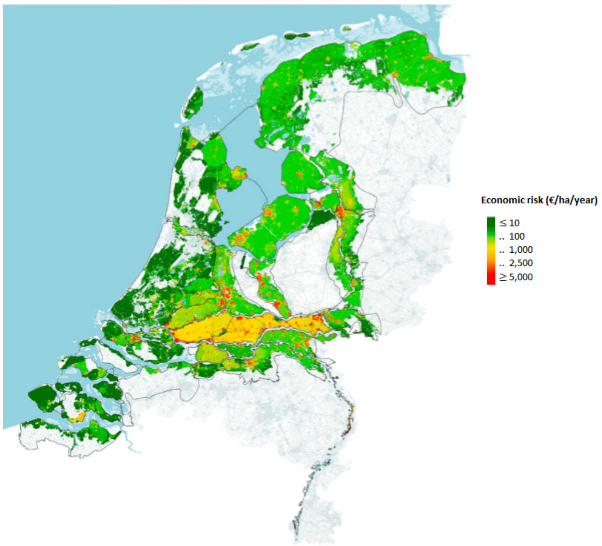


Figure 1.1: Annual expected value for economic losses per hectare (economic flood risk) in the Netherlands (source: Rijkswaterstaat, 2016)

Many studies have been done into mapping the economical flood risk (Jonkman, Bočkarjova, Kok, & Bernardini, 2008; Rijkswaterstaat, 2016). Figure 1.1 shows a map of this risk in the Netherlands. The magnitude of the risk is determined by the flood probability and the economic value of the location. The economic value influences the potential economic damage that a flood event can cause. From the figure it turns out that major Dutch cities like Amsterdam and The Hague are well protected. The high economic value in these cities is not visible in the flood risk map. In the river areas of the Netherlands, the economic risk is higher. Here, flood adaptation measures could be a solution.

In order to find the best measure, a cost-benefit analysis (CBA) is often applied. Each measure results in an (economic) risk reduction, which forms the benefit. The residual risk and measure cost combined are the total costs. Favorable adaptation measures have low total costs (Figure 1.2) and have an acceptable protection level. The measure with the lowest total costs is not always the best measure. This is shown by the benefit-cost ratio (BCR). The risk reduction relative to the cost is decisive for this indicator (see Section 3.2). The method from the Figure 1.2 was firstly applied by Van Dantzig (1956) after the Watersnoodramp, which is the largest flood disaster in the Netherlands in the 20th century. As a consequence, more than 1,800 people died. After the Watersnoodramp, the Deltaplan was set up, which lasted until 1997 (Rijkswaterstaat, 2018). The method helped to determine the optimal height of flood defenses part of the Deltaplan. It is still an important element in the choice of flood adaptation measures.

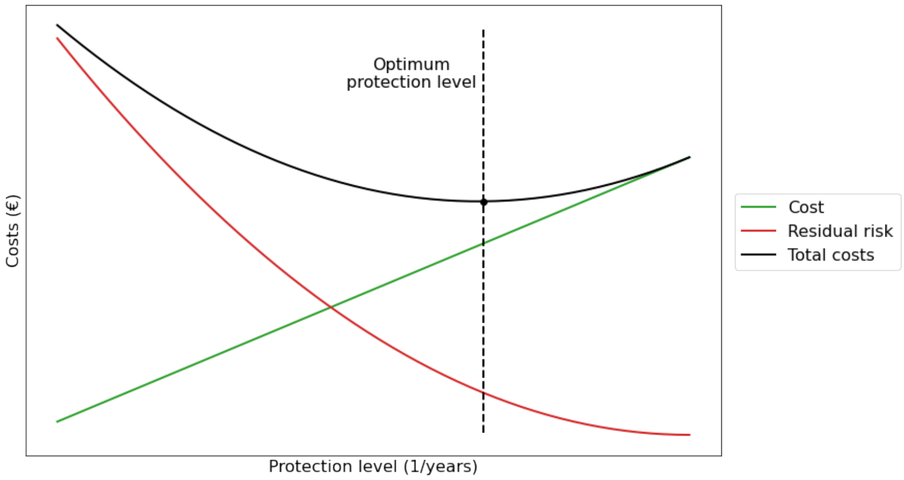


Figure 1.2: Conceptual plot of the cost, residual flood risk and total costs. The optimum is the protection level for which the total costs are lowest.

1.2. Problem description

In the general introduction it was mentioned that comparing measures often is supported by a cost-benefit analysis. Royal HaskoningDHV (RHDHV) also carries out this analysis to determine the correct measure strategy, which is processed in consultancy reports (for example Royal HaskoningDHV, 2020b). The current method used for this is analytical. This means that the method is time-consuming when multiple measures have to be screened. In addition, it is not very reproducible and sensitive to errors. In case of errors, it again takes a lot of time to implement the corrections. A quick supporting tool to screen measures can be a solution for this.

The Global Flood Risk Tool (GFRT) is an online tool developed by RHDHV. The tool can be used to calculate economic damage maps and risk maps. The input for the GFRT are inundation maps, a land use map and damage functions. The inundation maps can be obtained as output of a hydraulic model, or can be calculated based on extreme water levels from a statistical database projected on a Digital Terrain Model. Therefore, the tool does not focus on hydraulic modelling, which is an input, but does focus on impact modelling. The possibilities of the GFRT are increased when the effects of measures are also calculated. In the current GFRT this is only possible manually, by using an alternative input. As described in the previous paragraph, this is time-consuming.

More generally, the mentioned problem of measure screening has existed for a couple of years. Because of that, there have already been found some solutions. Some solutions contain the use of an alternative analytical method, which can be based on formulas (Van Ledden, 2016; Lendering, 2018) or on an analytical framework (Lendering, Sebastian, Jonkman, & Kok, 2018). The disadvantage of such solutions is that those are quite theoretic and hard to implement or grasp. More complex situations in practice are difficult to evaluate by using these solutions. In addition, other solutions have been developed in the form of models and tools (see for instance Van Berchum, Van Ledden, Timmermans, Kwakkel, & Jonkman, 2020; DHI, 2020). These applications can make representative simulations and are applicable in practical situations. However, the output of the existing models and tools is not directly in line with the current RHDHV method, in which a more extensive cost-benefit analysis is carried out. Therefore, the strengths of these methods can be of value, but a new, fast solution is needed for screening measures that is in line with the method of RHDHV.

1.3. Objective

From the problem definition it appeared that an alternative method for the screening of flood adaptation measures is required, with respect to the analytical approach of RHDHV. An economic flood risk-based framework is the chosen method for this. The framework, which is programmed in Python, should perform automatized calculations of the costs and benefits of adaptation measures without the need for hydraulic simulations per measure. Because no additional hydraulic simulations are used and time is limited, the framework contains eleven adaptation measures. These measures are given in Section 2.2. The framework is intended to be applicable on any location of interest in the world. Moreover, the intention is to integrate the framework into the online Global Flood Risk Tool. This leads to the following main research question:

How can flood adaptation measures be screened within the risk-based approach to evaluate a list of possible measures without hydraulic modelling each measure?

The sub-questions that contribute to the main research question are:

1. **What are the current methods for comparing flood adaptation measures and what are the strengths of these methods?**
   With answering this sub-question, the earlier mentioned existing methods that can compare flood adaptation measures are further analyzed. These methods include the analytical approach of Royal HaskoningDHV, alternative analytical methods, hydraulic models and tools. The benefits of these methods are important to consider in the composition of the functional requirements.
2. **What are the functional requirements for the framework?**
   Partly due to the analysis of existing methods, the functional requirements for the framework can be composed. Here it is also important to formulate the constraint for the framework's functioning. The measures that can be included in the framework should be made specific here. The functional requirements form a guideline for developing the desired end product.
3. **How can the framework be applied to a real case location?**
   Initially, the framework is – based on the functional requirements – elaborated in a conceptual form. Because the intention is to make the framework applicable worldwide, the framework is applied to two interesting case locations. The case locations are based on areas for which Royal HaskoningDHV made consultancy reports in the past. Therefore, the outcomes of the framework can be compared to the results of the existing analytical measures screening method.

1.4. Report overview

This introducing chapter described the broader context of this thesis. Also, the objective and research questions were mentioned with a substantiation in the problem definition. In the next chapters, the elaboration of the thesis follows based on the mentioned sub-questions. Chapter 2 takes a closer look at the existing methods for comparing flood adaptation measures. It is also checked which commonly applied adaptation measures can be used in the framework. The chapter concludes with the functional requirements and the constraints for the framework. Chapter 3 is about the design and functioning of the new framework. Important here are the connection with the risk calculation from the existing Global Flood Risk Tool and the effects and costs of the included measures. The functioning of the framework is substantiated by an application on two fictional cases. In Chapter 4 the framework is applied to Phu Loc (Vietnam) and in Chapter 5 the framework is applied to the Waalhaven and Eemhaven (Rotterdam, the Netherlands). The results of these case simulations are compared to the earlier findings from consultancy reports of Royal HaskoningDHV. The conclusions of this thesis, containing the answers to the research questions, can be found in Chapter 6. Finally, the discussion as well as the recommendations are given in Chapter 7.

2

Background

In this chapter, the already existing methods for prioritizing measures are analyzed. Examples of methods are the current decision method of Royal HaskoningDHV, analytical methods and numerical models and tools (Section 2.1). In Section 2.2, adaptation measures are chosen for implementation in the framework. Finally, the functional requirements of the framework are composed in Section 2.3, based on the findings from the existing methods.

2.1. Existing methods

This section presents the methods that already exist before the development of the measures framework. First, the current method of Royal HaskoningDHV for prioritizing adaptation measures is described (Subsection 2.1.1). Thereafter, other methods are discussed. These methods are subdivided into analytical methods (Subsection 2.1.2) and numerical methods (Subsection 2.1.3).

2.1.1. Current method Royal HaskoningDHV

The consultancy firm Royal HaskoningDHV has much experience with prioritizing different civil engineering solutions. Therefore, the company is often asked to give advise on the flood adaptation measures that should be imposed. Currently, the typical elements of such consultancy projects are collecting the required data of the area, producing maps and graphs for the current situation and identifying the most important measures and locations (Royal HaskoningDHV, 2018a, 2020b, 2020c, 2020d). The application of the current Global Flood Risk Tool (GFRT) helps in finding the critical locations in terms of flood risk. Apart from the GFRT, this method is performed analytically.

After the production of the current risk map, a long-list of adaptation measures is composed based on the existing planned measures and the risk assessment. This list contains in the order of thirty possible measures. Following the Multi-Level Safety (MLS) approach, the measures are categorized. MLS approaches flood safety in three layers: prevention, spatial planning and improved emergency management (Deltares, 2013). By means of go/no go criteria in terms of feasibility and effectiveness, the long-list of measures is reduced to a short-list (Royal HaskoningDHV, 2018a, 2020b, 2020c, 2020d).

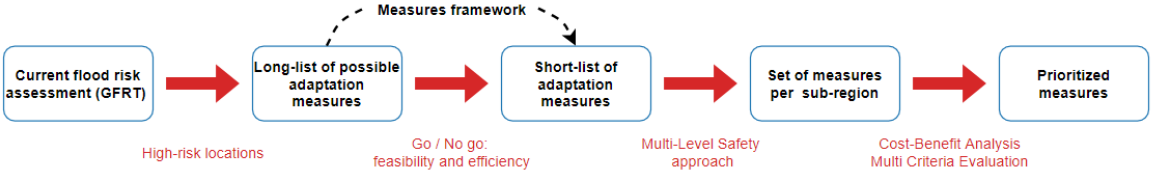


Figure 2.1: Phases and steps of the current measure decision method of Royal HaskoningDHV (based on Royal HaskoningDHV, 2020b)

From the obtained short-list, a set of measures are proposed following the MLS approach for each sub-region. These are further elaborated by conceptual designs and cost estimates. The physical measures, regarding the first two layers of the MLS approach, are prioritized by a cost-benefit analysis (CBA) and a multi criteria analysis (MCA).

In the CBA, there are three key performance metrics used. The first one is the net present value (NPV). The NPV is the absolute difference between the benefits and the cost, summed up over the considered time horizon. The second key metric is the internal rate of return (IRR). The IRR is the discount rate for which the NPV of the costs and benefits results to zero. The higher the IRR, the more effective the measure, as the value reflects the effectiveness of the investment. Thirdly, the benefit-cost ratio (BCR) is a key metric. The BCR is the benefits divided by the costs, both summed up over the considered time horizon. This can be seen as the relative difference between the benefits and costs. If the NPV for a measure is positive, the benefits outweigh the costs. In that case, the BCR is also higher than 1. This also means that the IRR is higher than the used discount rate in the cost-benefit analysis.

In the MCA, scores are given to criteria, which are proposed based on the location. Considered criteria are about planning, economics, socio-economic effects and environment (Royal HaskoningDHV, 2020c), which form the other risk categories mentioned in Section 1.1. As the expression in monetized terms is more concrete, the MCA is regularly used as a support for the results of the CBA.

Usage of the framework is intended for the phase in which the initial list of measures is reduced (see Figure 2.1). This is the phase in which the measures are screened. The framework can be used as a support for the existing analytical method of RHDHV, for quick and insightful screening of measures and protection levels in different sub-areas. Currently, the optimal protection level is not determined per measure, which the framework could take into account. Because not all measures can be simulated by the framework, the existing method of RHDHV is still important to analyze measures that are not included. Moreover, the feasibility of measures is not considered by the framework, which is also important in the reduction of the long measure list.

2.1.2. Analytical methods

In the following paragraphs, two analytical methods are described that can prioritize different flood adaptation measures. The first method focuses on levee systems and landfills only, while the second method is more general. Both approaches can be found in the dissertation of Lendering (2018).

Formula approach

Recently, Lendering (2018) developed an analytical approach for finding the costs and benefits of levee systems and landfills (see also Van Ledden, 2016; Royal HaskoningDHV, 2017). Investments in a levee system can be related to the circumference of the area of interest, while the investments in landfill can be related to the area itself. This means that, dependent on the area, there is a difference in the costs per strategy. This is shown in Figure 2.3: for smaller areas, the costs of a landfill are lower than the costs of a levee system and vice versa for larger areas.

The length of the levee system, which is the circumference of the area of interest, can be simplified. This is done by assuming that the area is circular, this leads to $L = 2 \cdot \sqrt{A \cdot \pi}$. The investment cost for a levee system can be described with the following equation:

$$I_{\text{levee}} = L \cdot h_f \cdot C_f \approx 2 \cdot \sqrt{\pi \cdot A} \cdot h_f \cdot C_f \tag{2.1}$$

Where:

L [m] = Length of the levee system
h_f [m] = Design height of the levee system
C_f [€/m/m] = Marginal cost levee system
A [m^2] = Area

The investment cost for a landfill measure can be described as follows:

$$I_{\text{landfill}} = A \cdot h_l \cdot C_l \tag{2.2}$$

Where:

h_l [m] = Design height of the landfill
C_l [€/m^2] = Marginal cost landfill

As described in Section 1.1, the flood risk consists of the probability and the consequence. In the case of economic risk, the consequence is equal to the economic damage. For a simple relationship between the flood depth and the damage, Lendering uses the following linear relationship:

$$D = D_{pot} \cdot \frac{d}{d_{max}} \tag{2.3}$$

Where:

D [€] = Economic damage
D_{pot} [€] = Potential economic damage
d [m] = Inundation depth
d_{max} [m] = Maximum inundation depth

The area multiplied by the land value is the potential economic damage ($D_{pot} = A \cdot LV$ with LV in €/m^2). This damage is reached when the inundation depth d is greater than the maximum depth d_{max}. With Equation (2.3) and a probability distribution for the inundation depth, the economic flood risk can be calculated. Van Dantzig (1956) used an exponential distribution for this. For the flood risk, formulas have been derived for both the levee and the landfill measure. These relations are different, because the consequences of a flood differ per measure. The flood risk of the levee system exists for the case that the water level is higher than the design water level of the system. Here it is assumed that the entire area gets flooded and the water level is the same everywhere. For the landfill measure, flood risk also exists for the scenario that the water level increases to above the design level of the landfill. The inundation depth is lower in case of the landfill due to the higher ground elevation (see Figure 2.2).

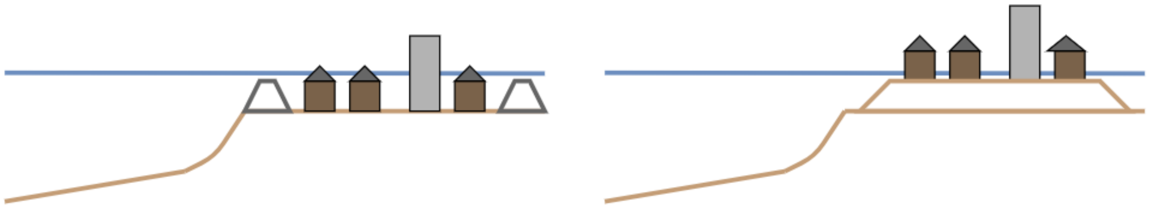


Figure 2.2: Consequences of flooding of the area with a flood defence system (left) and a landfill (right). The inundation depth is lower in case of a landfill.

The derived risk relations for both measures show a linear relations between the surface area of the area and the flood risk (Lendering, 2018). As mentioned in Section 1.1, the total costs are the sum of the (investment) cost and the remaining risk. Using the formulas, the relation between the area and the total costs has been derived for both measures. This relation is shown in Figure 2.3. The transitional area represents the area for which the total costs for both measures are equal. Interestingly, the landfill measure is more effective for small areas and the levee measure is more effective for large areas. The graph in Figure 2.3 shifts for other variables (cost units, land value and water levels). By using this method, levees and landfill measures can be compared with little data. However, this simplifies reality much and the method only works for two measures.

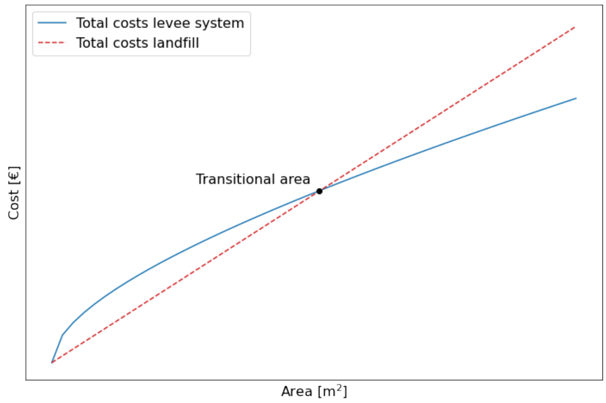


Figure 2.3: Total costs of a levee and landfill measure as a function of the area (based on Lendering, 2018)

Performance framework

The second analytical method (Lendering et al., 2018) and also part of the dissertation of Lendering (2018), is about a performance framework that can be applied for any adaptation measure of interest. The performance of each measure is determined by four performance indicators: efficiency, durability, reliability and cost. The implication of those indicators is described in the following paragraphs.

The effectiveness of the measure is expressed in reduced flood risk. Since the flood risk is the product of the probability and the consequences (Equation (1.1)) this can be achieved by a reduced flood probability or reduced consequences (damage). Measures that reduce the flood probability have effect on the water levels or inundation depths, while damage reducing measures affect the damages as a consequence of the inundation depths.

The durability or lifespan of the measure determines for how long the measure can fulfill its function. Not every measure has the same lifetime as the entire considered time horizon, so replacements might be necessary during the period. Important aspects of the durability are the operational moments (continuously or temporarily) and the number of applicable times (single or repetitive use). However, this could also be included in the maintenance cost. A short lifetime of measures is simplified to high maintenance cost in that case.

The reliability is the probability that the measure fulfills its function during its lifetime. This is quantified by the probability of failure P_f. This probability is considerable especially for temporary emergency measures due to possible detection, placement and construction errors (Lendering, Jonkman, & Kok, 2014). In overall, the failure probability is hard to make estimations of. Adaptation measures are designed conservatively in practice to deal with this probability.

Finally, the cost includes the investment of the measure, consisting of the purchase, installation, operation and management cost over the lifetime. The purchase and installation are initial costs, while operation and management form costs that are present during the entire lifetime of the measure.

2.1.3. Models and tools

Apart from analytical approaches, hydraulic models and tools were developed that assess the effects of flood adaptation measures numerically. The tools also use hydraulic models to run the simulations. Some examples of models and tools for comparing adaptation measures are described in this subsection.

FLORES
The FLORES model was applied to the city of Beira in Mozambique (Van Berchum et al., 2020). In Beira, eleven measures are considered: heighten the dunes at two locations, sand supplements in the east, flood wall in the west, heighten an inland road, second phase drainage, micro-drainage, retention at two locations, improve evacuation and an early warning system. Besides, different heights and sizes of these measures are considered.

FLORES divides the city into multiple drainage basins. For each basin, the volume balance of the water inside is important. If the water volume in the basin is higher than the storage volume, the area inundates. Storms can be simulated by increasing the sea water level and therefore the discharge from the sea into the system. Rainwater runoff is also an inflow source. Flood defences can be placed on the borders between different basins. If a flood wall is present at the coast, inflow discharges are reduced. Only if the flood wall fails, the same inflow discharges occur as without the measure. If water retention is applied, the storage volume of the corresponding basin increases, so inundation becomes less likely. The applications of combinations of different adaptation measures are important in the model. In total, FLORES considers 500 strategies of combinations.

From the maximum inundation depths and the land use, the economic damages are calculated with stage-damage functions (Jonkman et al., 2008). Also, the expected number of affected people by the flood is calculated. Thirdly, the model calculates the construction and repair cost of the measures. The maintenance cost is not calculated separately. By means of feature scores, the relative importance of the measures and input variables on the three mentioned outputs is determined. The final step of FLORES is identifying the efficient measure combination strategies. This is done by the Patient Rule Induction Method (PRIM). This method is meant for reducing the number of measure combinations. Prior to the analysis, a criterion is given for the measure combinations. The PRIM algorithm calculates the combinations that fulfill this criterion and which measures are most common in these combinations. These measures seem to be most efficient. Combinations where those measures are missing, are filtered out of the list as well. The most efficient measures and the remaining combination strategies form the output of this analysis.

Adaptation Support tool
In order to help cities with finding resilient solutions for climate hazards, Deltares developed the Adaptation Support Tool (Deltares, 2019). This tool helps the stakeholders to come to an optimal set of adaptation measures. It is an interactive tool that could be used during stakeholder meetings and could also be used by less experienced users. More than 50 measures are included in the tool. In Figure 2.4, an overview of the tool is given. On the left, the selected measures are shown. The spatial planning of these measures can be observed on the map in the middle. The results of the combination of measures are presented on the right.

Results

Climate
Storage capacity: 15204 m3
Return time factor: 52.94 +1
Groundwater recharge: 176 mm/year
Evapotranspiration: 351 mm/year
Heat reduction: 0.07 C
Cool areas: 1

Cost
Construction: 11806315 €
Maintenance: 506120 €/year

Water quality
Pathogen reduction: 31.13 %
Nutrient reduction: 7.06 %
Adsorbing pollutants: 31.26 %

Figure 2.4: Overview of the layout of the Adaptation Support Tool of Deltares. The left panel shows the selected measures, the map in the middle presents the spatial planning and the right panel gives the results of the applied measures (source: Deltares, 2019).

The effects of the measures are calculated by an underlying hydrologic model. Important is that the purpose of this tool is not directly reducing the flood risk. Effects of adaptation measures in this tool are therefore not relevant for this thesis.

FloodRisk

DHI is a Danish research institution and has similarities with the Dutch Deltares. The institution developed FloodRisk, which is another tool that visualizes the risk effects of different adaptation measures (DHI, 2020). FloodRisk is web-based and makes use of an underlying flood model for the generation of inundation maps. The tool is interactive, because the user can select adaptation measures and the location of the measures. The tool has a clear layout, it is easy to understand for less experienced users (see Figure 2.5). The output is extensive: maps and tables can be downloaded from all the steps of the risk calculation.

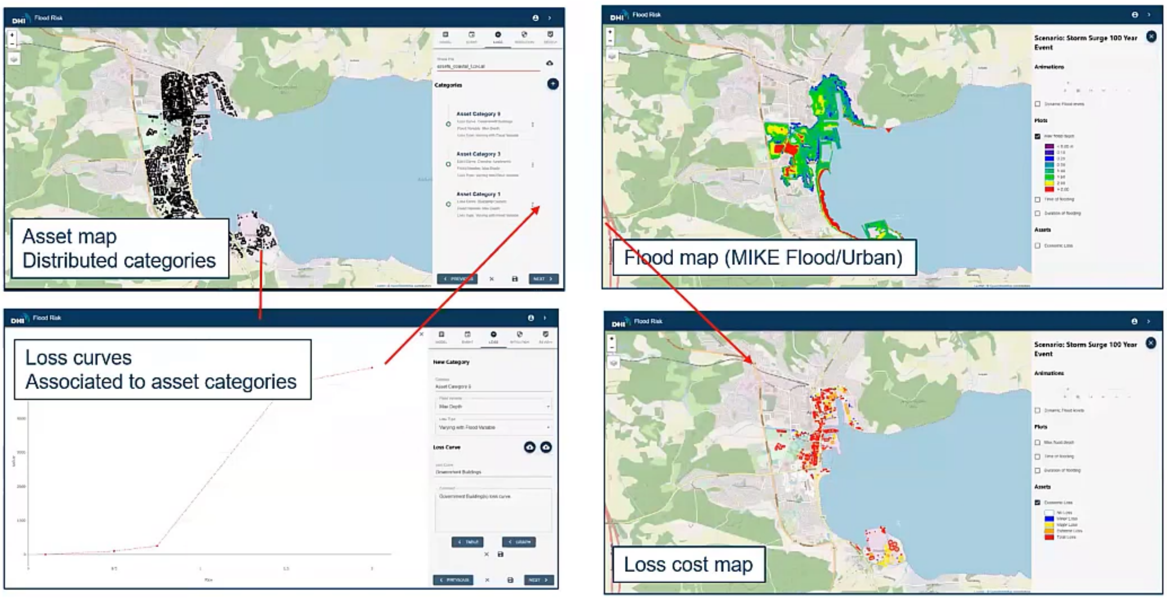


Figure 2.5: Overview of the FloodRisk tool (source: DHI, 2020)

For the calculations, this tool uses dynamic hydraulic modelling. In dynamic modelling, the inundation maps vary over time instead of simple, static inundation maps. Dynamic modelling is advanced and can increase the calculation time compared to static modelling. Although dynamic modeling provides an extra dimension, static modeling is sufficient for screening measures. More detailed effects per measure can be found in a later stage of the measure selection.

Flood Modeller

The firm Jacobs developed the Flood Modeller, a program that can simulate floods in 1D, 2D and combined grids (Jacobs, 2020). The program is mainly focused on river floods. The simulation program is offline and should be installed before using it. Figure 2.6 shows the general user interface of the Flood Modeller. From the hydraulic model results, the damages and economic flood risk can be calculated by the program. However, the results of the Flood Modeller can be analyzed in the online Flood Viewer. In this way, users with less experience in flood modelling can also view the results. These results can be viewed in map form.

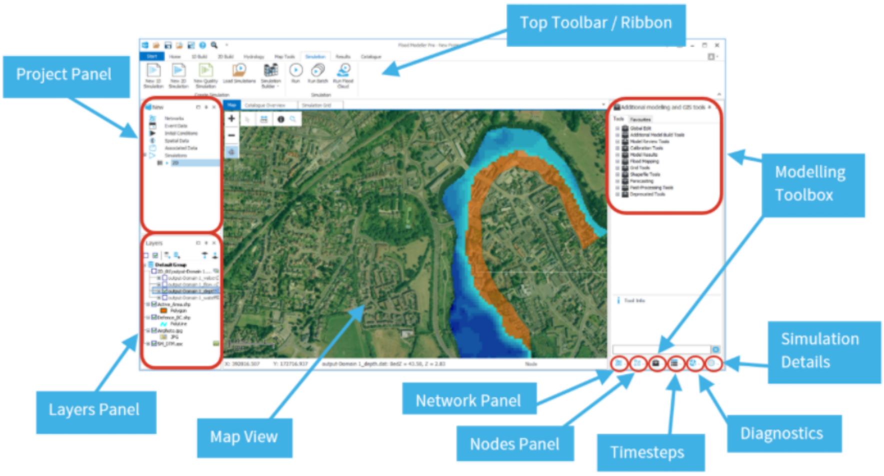


Figure 2.6: General user interface of the Flood Modeller (source: Jacobs, 2020)

Although the Flood Modeller is multi-functional, the implementation of adaptation measures is more complicated. This requires enough knowledge of modelling floods, since the measures should be implemented by changing the initial landscape. This tool is therefore less suitable for screening measures when detailed designs of adaptation measures are still missing.

Aqueduct Floods

The World Resources Institute (WRI) also developed a flood simulation tool with adaptation measures (World Resources Institute, 2020b). This tool is called Aqueduct Floods and operates online. The tool considers multiple climate change scenarios and future climate impacts. Risk forms that are calculated by the tool are the affected population and affected assets (absolute and relative to the total value). The underlying model GLOFRIS is used to calculate the inundation depths for riverine floods. Coastal floods are assessed separately from riverine floods and these hazards are estimated by an extreme value analysis of Global Tide and Surge Reanalysis (GTSR) data. The flood risk is calculated for four moments in time: in 2010 (base situation), 2030, 2050 and 2080. Flood protection measures can be applied for different design return periods. With damage graphs, showing the economic against the flood probability, the economic risk is calculated. The results are clearly visualized by risk graphs that show the protected and non-protected expected annual damages (Figure 2.7).

An important missing element of Aqueduct Floods is the possibility to apply multiple types of adaptation measures. The current tool only considers levees as an intervention. This also means that combinations of measures cannot be analyzed by this tool. The output of the tool is pre-calculated, which means

Select a location: Vietnam

Compare with: Compare with...

Select a future scenario: Business as usual

Design Protection Level (Return Period): 25

Target Year for the Design Protection Level: 2050

Figure 2.7: Overview of Aqueduct Floods (source: World Resources Institute, 2020a). The tool can be used for expected inundation levels (Hazard), expected consequences (Risk) and the effects of measures (Cost-Benefit Analyzer). The output of the measures analyzer is in the form of graphs.

that it cannot perform new calculations. The results are in the form of graphs but are barely presented in a map form. Only a single inundation map is shown after application of the measure. For a complete comparison of adaptation measures, it is important for users to find out what the spatial effect of the measures is on the area of interest.

2.1.4. Conclusions

On the basis of the above mentioned existing methods, the strong and missing elements can be put together. The interesting elements from the existing methods and tools that will be used in the framework are as follows:

- In the analytical method used by Royal HaskoningDHV to screen measures, the costs and benefits are important. This is also the intention of the framework. Several key performance indicators are calculated from the costs and benefits. These are the net present value, internal rate of return and the benefit-cost ratio. The indicators can directly give the degree of effectiveness of the measures.

- With the analytical formulas from Lendering (2018) and Van Ledden (2016) the optimal areas for measures were found by calculating the total costs. The total costs are the sum of the investment and operation and maintenance (the direct cost) and the residual risk. The graphs containing the total costs give a quick indication of the optimal measure variants. Because the derived formulas are not well applicable in practical situations, these are not used in the framework.

- An element of the performance framework developed by Lendering et al. (2018) is the efficiency, which is expressed as the risk reduction. Two kinds of measures are distinguished: measures aimed on failure probability reduction and measures aimed on damage reduction. This distinction is useful for the application of measure effects. Probability-aimed measures can be seen as measures that have effect on the inundation maps. On the other hand, consequence-aimed measures are the measures that have effect on the damage functions and land use map.

- The Aqueduct Floods tool (World Resources Institute, 2020b) contains damage graphs. The economic damage is shown as a function of the flood probability here. The area below this graph represents the flood risk. The graph gives a view on the effect that a measure has on the flood risk. This effect is different per measure type. Probability reducing measures are expected to lower the damage for high flood probabilities, while consequence reducing measures can reduce the high damages with lower probabilities.

- FLORES (Van Berchum et al., 2020) contains useful measures, especially water retention. The model calculates the inundation depths from the water balance. Areas are flooded when the present water volume exceeds the capacity volume. This capacity is increased with the retention measure. Therefore, the inundation is reduced by the retention storage volume divided by the area.

- An element of the output of the Adaptation Support Tool (Deltares, 2019) are the given quantities of measures, based on the selected location. The cost calculation can be better understood with the given measure quantities.
- In the Adaptation Support Tool (Deltares, 2019), FloodRisk (DHI, 2020) and Aqueduct Floods (World Resources Institute, 2020a) it is possible to select an area where the measures are applied in an interactive way. The area selection function makes these tools also usable for less experienced users.
- The tools FloodRisk (DHI, 2020) and Flood Modeller (Jacobs, 2020) can show risk maps as an element of the output. The risk maps show the spatial effect of the measures on the flood risk. From these maps it can be observed whether the measures reduce the risk sufficiently to be acceptable in the entire area.

The missing elements from the existing tools are:

- The tools give possibilities to change some of the parameters in the calculation. The desired broad applicability of the framework means that these parameters can be very different per location. Therefore, it is useful to list all the parameters from the calculation and make those adjustable.
- None of the tools shows the uncertainty of the results. The uncertainty can be caused by for instance the inundation depths, damage functions and measure cost. Accurate information is not always available during the screening of measures. An uncertainty analysis can give insight into the range of the results. A suitable performance metric to represent in uncertainty is the net present value. This metric is directly related to the effectiveness, because the higher the outcome the better the effectiveness. In addition, the NPV is concrete, because it is expressed in money. The degree of uncertainty can also be used as a criterion in the assessment of the measures, apart from the costs and benefits.
- Since certain elements are missing in each method analyzed, bringing the strong elements together can lead to a good new tool. This is the starting point for the framework.

2.2. Measure selection

This section is about the delineation of the framework in terms of possible adaptation measures. The used measures from the existing methods and tools are given in Table 2.1 and are described shortly in this section. For some of the tools only the known included measures are mentioned. The measures living shoreline, wet proofing and elevating buildings are added to the considered measures. These measures are mentioned by De Moel, Van Vliet, and Aerts (2014) and New York City Department of City Planning (2013).

Table 2.1: Included flood adaptation measures in the existing methods and tools

Method/tool	Included measures
Analytical formulas	Levee system, landfill, dry proofing
Performance framework	Levee system, flood walls, dams, delay rainwater runoff, retention, storm surge barrier, breakwaters/groins, nourishments, temporary barrier, early warning system, insurance, subsidies, education
FLORES	Flood walls, retention, early warning system, nourishments
Adaptation Support Tool	Levee system, retention, delay rainwater runoff, temporary barrier
FloodRisk	Levee system, retention, early warning system
Flood Modeller	River widening, breakwaters/groins
Aqueduct Floods	Levee system

The descriptions per measure as well as the reasons for (not) including the measures are given below.

- **Levee (dike) system**
  With this measure, the area of interest is protected by surrounding levees. These prevent flood water from flowing into the area. This measure is appropriate for the framework, because all the water in the area can be removed for milder flood scenarios than the protection level.

- **Flood walls**
  When flood walls are constructed, flood water from outside the area of interest can no longer reach the area. Therefore, the effect of flood walls in framework would be the same as for a levee system. This means that implementing flood walls does not have an additional value.

- **Storm surge barrier**
  A storm surge barrier could limit the flood effects for larger areas. However, such a barrier cannot be placed in every situation. The determination whether a storm surge barrier can affect the inundation in a certain part of the area cannot be done by the framework.

- **Dams**
  These structures are located at upstream locations and influence the river discharge. Because there is no additional hydraulic modelling, effects of a river discharge reduction cannot be found by the framework.

- **Breakwaters/groins**
  The purpose of these structures is to reduce the impact of currents and waves. The framework cannot simulate changes in currents and waves because there is no hydraulic modelling.

- **Nourishments**
  Nourishments increase the strength of coastal systems and are especially effective in low-lying coastal areas with a large availability of sand (New York City Department of City Planning, 2013). Therefore, this is a specific measure. Also, the local wave climate and bathymetry determine how the nourishment develops and what the risk reduction would be. This cannot be quantified by the framework.

- **Landfill**
  With a landfill, the area of interest is elevated wherefore the resistance increases against high water levels. Because a landfill directly leads to lower inundation depths, this measure is appropriate for the framework.

- **Retention**
  With retention, transportation and storage of water in a retention area or polder is meant. A good drainage system that collects and transports the water can lead to a direct decrease in inundation depths. Therefore, this measure can be included in the framework.

- **Delay rainwater runoff**
  The intention of this measure is to increase the storage capacity of the subsoil, wherefore rainfall leads to floods less frequently. For areas that are vulnerable to pluvial floods, a reduction can be applied to the flood inundation depths. Thus, this measure is appropriate for the framework.

- **Living shoreline**
  A living shoreline is meant to lower the force of waves and storm surge on the coast and stabilization of the shoreline (New York City Department of City Planning, 2013). This reduces the flood depths in coastal flood scenarios. By assuming a simple reduction factor on the flood depths, this measure can be considered in the framework.

- **River widening**
  Creating a wider riverbed leads to lower river water levels. However, the rate of decrease depends on river characteristics that cannot be deducted from inundation depth maps. Also, the influence of a lower river water level on the surrounding area cannot be quantified without a hydraulic model.

- **Dry proofing**
  With the application of dry proofing, buildings are protected by a wall or panel. Flood damage is then only present for higher water levels than the level of this protection. Such an effect can be modelled by modifications to damage functions, therefore dry proofing is appropriate for the framework.
- **Wet proofing**
  Wet proofing means the change of layout of buildings, wherefore the vulnerable elements are not immediately exposed to flood water (De Moel et al., 2014). This effect can be applied on the damage functions within the framework.
- **Elevating buildings**
  By elevating buildings the flood damage is greatly reduced. The elevation can be directly related to the reduction of damage functions (De Moel et al., 2014), meaning that this measure is appropriate for the framework.
- **Relocation/retreat**
  The strategic change of land use in an area has much reducing effect on the economic flood damages (New York City Department of City Planning, 2013). Relocation or retreat directly impacts the land use map, which can be modified within the framework.
- **Early warning system (EWS)**
  With the installation of an early warning system, affected people are warned on beforehand when a flood event is expected. The economic effect of such a system only has impact on the damage functions. Therefore, this measure is applicable for the framework.
- **Flood insurance**
  A flood insurance measure is very complex. The flood insurance premium is normally based on the current flood risk. Flood insurance companies should also make profit from the insurances. Therefore, for a screening of measures, the performance of a flood insurance cannot be found without major assumptions. It would be better to investigate these effects in a separate research.
- **Subsidies**
  Providing subsidies by the government could be an effective way to realize a relocation of high-risk assets, which is already another considered measure. The subsidy cost determination is also complex and outside the scope of the framework. The framework is namely focused on flood effects.
- **Education**
  This measure is very abstract. Education could improve the flood awareness of the people in the area. However, it is not clear how much the awareness could be improved. Also, the relation between the flood awareness and the damage reduction can only be found from estimates.

Therefore, the considered measures in the framework are a levee system, landfill, retention, delay rainwater runoff, living shoreline, dry proofing, wet proofing, elevating buildings, relocation and early warning system. More about the effects of these measures can be found in Section 3.3.

2.3. Functional requirements

This section presents the functional requirements of the framework. These requirements are based on the conclusions from the previous section. The elaboration of the framework where all requirements are considered can be found in Chapter 3. After the functional requirements, considerations outside the scope of the framework are given.

The functional requirements of the framework are as follows:

- The input of the framework consists of the following parts:
  - Initial inundation maps for the considered area, calculated by a hydraulic flood model

  - A land use map for the considered area
  - Initial damage functions for the land uses in the considered area
  - A data file that contains the cost estimates per measure and other input variables
  - An initial flood risk map for the considered area

- The framework should allow users to draw a region in which the effects measures are calculated and select the measures that need to be considered in the calculation. Moreover, the user should be able to adjust the input parameters, stored in a separate data file.

- The considered measures are a levee system, landfill, water retention, delay rainwater runoff, living shoreline, temporary barriers, dry proofing, wet proofing, elevating buildings, spatial redesign, and early warning system (see Section 2.2 for the argumentation). The framework should also be able to take combinations of these measures into account.

- The investment cost per measure should be calculated based on the selected region, design protection level and the cost estimates.

- The effects of the measures should be applied by adjusting the input data, without additional hydraulic modelling. The modifications of the input are in the form of multiplication with a reduction factor, replacement or subtracting. For the levee system, landfill, retention, delay rainwater runoff and living shoreline measures, the inundation maps are modified because these measures reduce the flood probability. The dry proofing, wet proofing, elevating buildings, relocation and improved evacuation measures modify the damage functions and/or the land use map. These measures namely reduce the consequences of flood events.

- With the investment cost and the risk reduction, the framework should calculate the following key performance indicators: total costs (TC), internal rate of return (IRR), net present value (NPV) and benefit-cost ratio (BCR). The TC and NPV should be calculated in million euros and the IRR and BCR should be found in decimals.

- The framework should contain an uncertainty analysis, which results in expected ranges of the net present value per measure strategy.

- The output of the framework should contain the following elements:
  - Maps per measure strategy that indicate the residual risk in the selected region
  - Damage graphs per measure strategy, showing the economic damage against the flood probability
  - Cost graphs per measure that show the possible design return periods against the investment cost, residual risk and total costs
  - A graph that contains the results of the uncertainty analysis in the form of boxplots per measure strategy
  - A table containing the required measure quantities per measure strategy, which supports the cost calculations
  - A table that contains the investment cost, risk reduction, the four key performance indicators and a ranking of the measure strategies

The following points are outside the scope of the framework:

- Other risk categories apart from the economic risk (socio-economic and environmental risk) are not considered. These risk forms should be considered in a later stage of the measure design process. This framework is only applicable in the first stage, where different measures are explored.

- Specific measures that have complicated effects on the inundation depths cannot be part of the framework, for example river widening. For this, hydraulic modelling is required.

- Failure probabilities of permanent measures are not considered. The designs of these measures should be chosen such that performance deviations are allowed. Therefore, the framework expects no failure probability for permanent measures in situations milder than the design scenario.
- The extent of the measures is restricted to the grid size of the inundation and damage maps. If the grid size is large, the results of the framework are less accurate.
- The optimal moment in time that one should invest in the adaptation measure is not a part of the framework. The time component can have influence on converting values to present values: a later moment of investment leads to a lower present value of the investment (see Veenman, 2019).

3

The framework

This chapter is about the working of the flood adaptation measures framework. In Section 3.1, the current Global Flood Risk Tool is discussed. Thereafter, the newly created framework is described. The input, considered measures and general output are mentioned (Section 3.2). More detailed information about the adaptation measures can be found in Section 3.3 and 3.4. This chapter does also contain the working of the uncertainty analysis (Section 3.5). An example of framework results is shown in Section 3.6.

3.1. Current Global Flood Risk Tool

In this section, the calculation steps of the current Global Flood Risk Tool (GFRT) are given, supported by a fictional example. Firstly, a location is needed for the application of the GFRT. In principle, this could be any location in the world. The tool makes use of inundation maps. Those maps show the maximum flood depth in the area during a flood event. Inundation maps can be created by a simple overlay method or by more advanced flood models. For both methods, a Digital Terrain Model (DTM) is required that contains the elevation of the area. For the fictional example, the overlay method is applied. The terrain of the example area is shown in Figure 3.1. The entire area is above the mean water level, but can be flooded in case of extreme water levels. The grid size is 25 x 25 m.

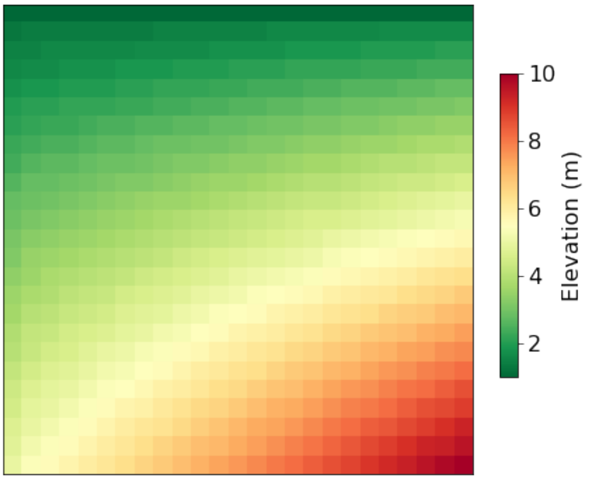


Figure 3.1: Elevation map of a fictional area (m)

With the given elevation map of the location, multiple floods are simulated. These floods are based on different water levels. In the overlay method, the extreme water level is compared to the elevation map. If the water level is higher than the elevation, the area is flooded. The inundation depth for the flooded areas is the difference between the water level and elevation. The water levels are coupled to certain return periods. The return periods are used for calculating the risk in a later step. In the example, three flood scenarios are simulated. The water levels are $h = 4$ m, $h = 5$ m and $h = 6$ m. The return periods are 10 years, 100 years and 1,000 years, respectively. Figure 3.2 shows the inundation depths in m for the flood scenarios from the example.

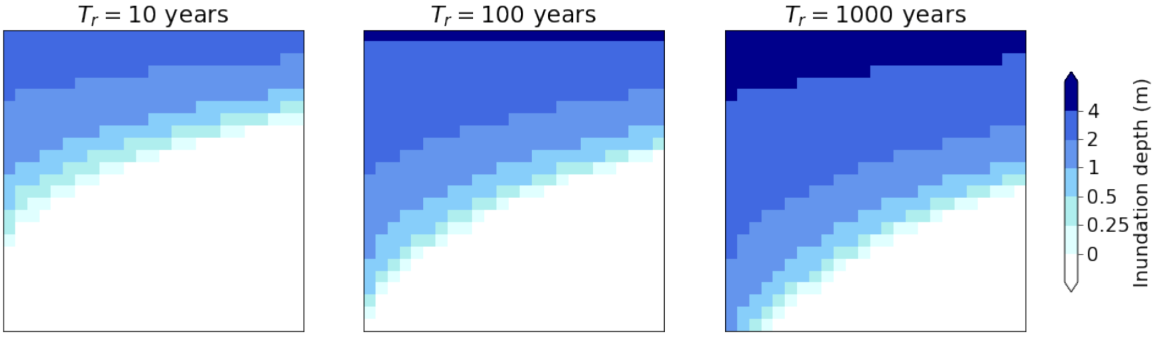


Figure 3.2: Inundation depth (m) for $h = 4$ m (left), $h = 5$ m (middle) and $h = 6$ m (right) of the example area

Besides the elevation map, a land use map is input for the risk calculation. This map indicates the function per location within the area, e.g. housing, industry or offices. Each included function has a representative land value: the economic value of the locations with that function. This value is important for calculating the flood damage. In the example, three different land uses are chosen. One land use has no value (€0/m^2), one land use has low value (€100/m^2) and one land use has high value (€1,500/m^2). The land use map of the example is shown in Figure 3.3.

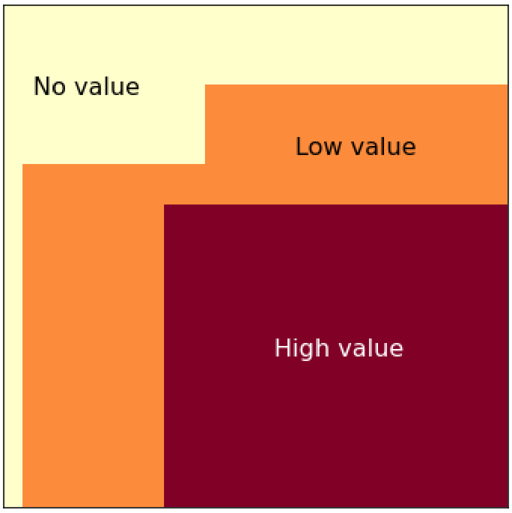


Figure 3.3: Land use map of the example. 'Low value' represents a land value of €100/m^2 and 'High value' represents €1,500/m^2.

Next, the inundation depth and land use are combined to calculate the damages in the area per flood scenario. The relation between inundation depth and damage is normally determined for inundation depths below the maximum depth. For greater depths, no additional damage occurs (like in Equation (3.1)). Below the maximum depth, the part of value that is damaged depends on the inundation depth. The dependency can be different per land use and form the final input of the GFRT. The presence of different damage functions is illustrated by the example: Figure 3.4 shows the relations for the low and high value land uses.

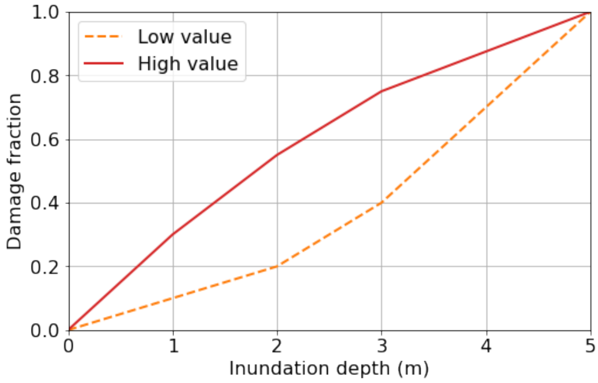


Figure 3.4: Damage functions for the example location, which form the relation between the inundation depth (m) and the part of land value that is damaged. The curves shown are for the low value land use (dashed line) and the high value land use (solid line).

To calculate the damage, the damage fraction that is obtained from the curve is multiplied with the land value. This must be done for every location on the map, because the inundation depth and land use are spatially variable. The equation to do so is as follows (based on Jonkman et al., 2008):

$$D(x,y) = \alpha_i\,(d(x,y)) \cdot D_{i,max} \tag{3.1}$$

Where:

x, y [m] = Location on the map
D [€/m^2] = Economic damage
α_i [-] = Damage function for land use i of the location
d [m] = Inundation depth
$D_{i,max}$ [€/m^2] = Maximum economic damage or economic value for land use i of the location

The damage calculation with Equation (3.1) is done for every flood scenario that is considered. The resulting damage maps give a quick insight into the critical locations within the area of interest per flood event. Figure 3.5 shows the damage maps of the example. Damages of milder flood scenarios seem to be negligible compared to those of extreme scenarios.

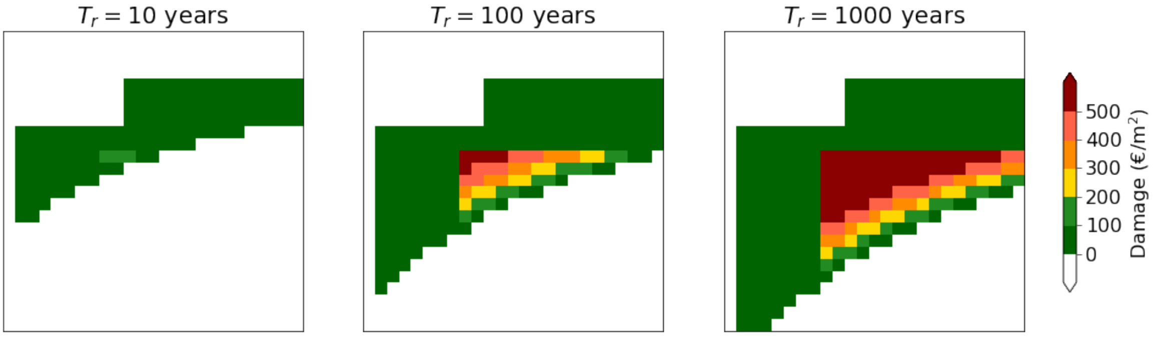


Figure 3.5: Damage maps (M€) for h = 4 m (left), h = 5 m (middle) and h = 6 m (right) of the example area

The damage maps shown in Figure 3.5 only contain the direct economic damages. A flood event can also cause indirect damages. Such damages could be outside the affected area, for example business interruption or effects to the supply chain that lead to loss of revenue at companies close to the affected area. In practice, the indirect damage is often assumed as a part of the direct damage. With this assumption, the total economic damage can be calculated as follows:

$$D_{tot} = D_d + D_{id} = D_d + (IDF - 1) \cdot D_d = IDF \cdot D_d \tag{3.2}$$

Where:

D_d [€/m^2] = Direct economic damage
D_{id} [€/m^2] = Indirect economic damage
IDF [-] = Indirect damage factor

If the indirect damage is assumed to be equal to the direct damage, the indirect damage factor is $IDF = 2$. Therefore, the total damage is then twice the direct damage.

The final step that is currently implemented in the GFRT is calculating the flood risk, which is the annual averaged damage (AAD) in the area of interest. This is done by combining the damage maps and the corresponding return periods. This is done by the following equation:

$$AAD = \frac{1}{2} \cdot \sum_{i=1}^{n} \left(\frac{1}{T_{r,i}} - \frac{1}{T_{r,i+1}} \right) \cdot (D_i + D_{i+1}) \tag{3.3}$$

Where:

AAD [€/year] = Annual averaged damage, expected damage per year
n [-] = Number of return periods
$T_{r,i}$ [years] = Return period for flood scenario i
D_i [€] = Economic damage for flood scenario i

This calculation is performed for every location or grid cell. In the example, three return periods were considered: 10, 100 and 1000 years. By using Equation (3.3), the annual averaged damage is then as follows:

$$AAD = \left(1 - \frac{1}{10}\right) \cdot \frac{D_{10}}{2} + \left(\frac{1}{10} - \frac{1}{100}\right) \cdot \frac{D_{10} + D_{100}}{2} + \left(\frac{1}{100} - \frac{1}{1000}\right) \cdot \frac{D_{100} + D_{1000}}{2} + \frac{1}{1000} \cdot D_{1000}$$

In the calculation it is assumed that damage can also occur for a return period shorter than 10 years (given in the first term of the expression). This is an important assumption and can lead to large differences with alternative risk calculations. Application of the expression leads to the risk map shown in Figure 3.6. The different land use areas are clearly visible. The critical location in terms of annual expected damage is the location with the highest inundation depths within the high value region. The total found flood risk in the area is $AAD = 2.5$ M€/year.

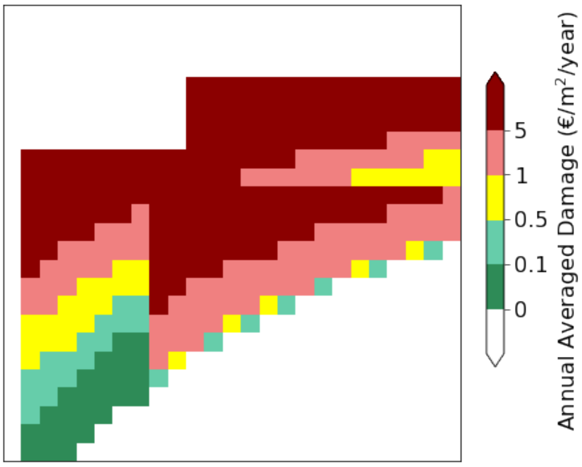


Figure 3.6: Annual averaged damage (€/m^2/year) in the example area

With the annual averaged damage, the present value of the flood risk can be calculated. This is a summation of all AAD values per year over the time horizon. It is performed as follows:

$$PV_{\text{risk}} = \sum_{t=1}^{T} \frac{AAD}{(1+r)^t} \tag{3.4}$$

Where:

PV_{risk} [€] = Present risk value
T [years] = Time horizon
r [-] = Discount rate

Application of Equation (3.4) with $T = 50$ years leads to:

$$PV_{\text{risk}} = AAD \cdot \left(\frac{1}{(1+r)^1} + \frac{1}{(1+r)^2} + ... + \frac{1}{(1+r)^{50}} \right)$$

When the discount rate is $r = 4\%$, this results in $PV_{\text{risk}} = 53.8$ M€ for the entire example area. In the following sections, the adaptation measures framework builds out on the given results. The creation of the measures framework is a part of this thesis.

3.2. Framework overview

This section provides the general procedure of the flood adaptation measures framework, which was developed as part of this thesis. This procedure forms a next step after the base scenario risk calculation from Section 3.1. The input, calculation steps and output are described. Subsequently, more information about the measure effects (Section 3.3) and cost (Section 3.4) as well as the uncertainty analysis (Section 3.5) can be found.

In the following paragraphs, the steps towards the output of the framework are described. Figure 3.7 shows a scheme of input elements, the different steps and the output elements. In the middle part, the calculations are performed for each measure variant. These variants depend on the selected adaptation measures and the return periods, which are part of the input.

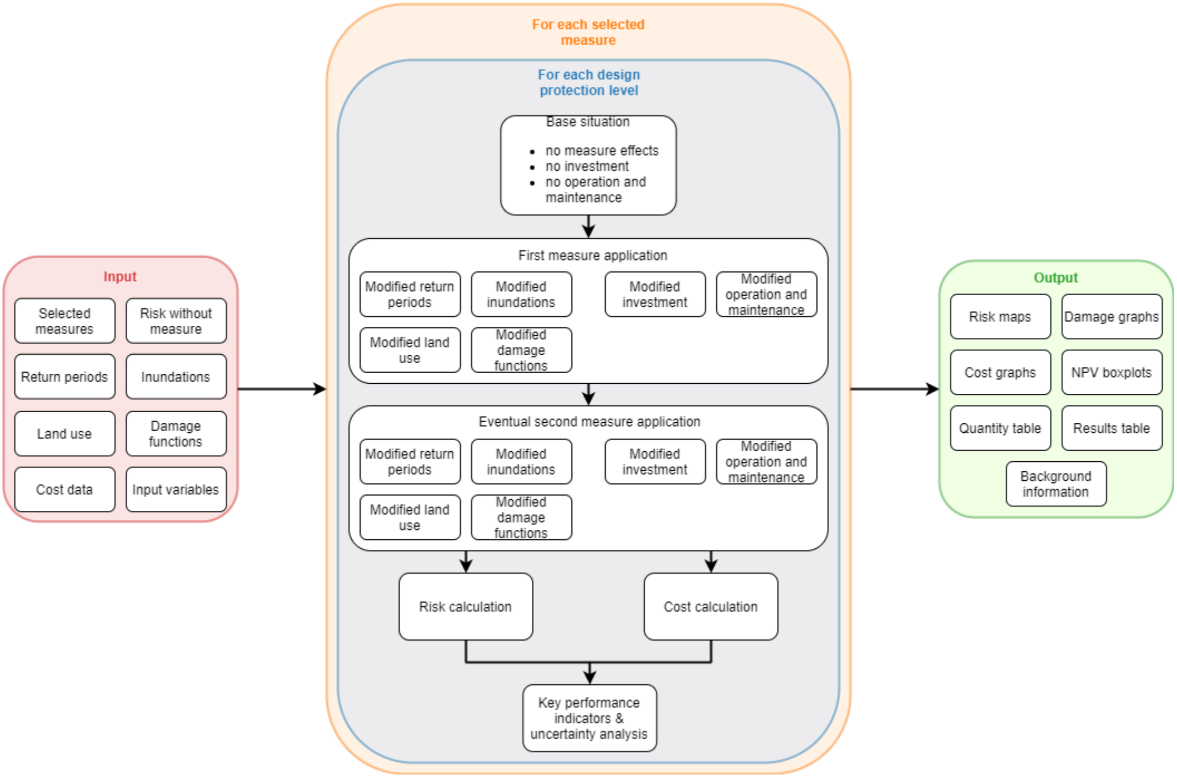


Figure 3.7: Scheme of the flood adaptation measures framework

When the framework is used, input is required. Once the area of interest is determined, the input consists of eight elements. These elements are as follows:

- **Selected measures**
  From the general list of measures in the framework, the user can select which measure(s) need to be taken into account. More information about the measures can be found in Section 3.3 and 3.4.
- **Risk without measure**
  The framework is an extension of a risk calculation without any adaptation measures (Section 3.1). Therefore, the risk without measure is available as input. It is in the form of a map, with the economic flood risk per location.
- **Return periods**
  Return periods are required when the flood risk is calculated. The return periods stand for the flood scenarios that are considered in the flood risk calculation. These can also be deduced from the risk calculation without measures and are in a list form.
- **Inundations**
  Per return period, an inundation map is required. This map shows the maximum water depths during an extreme flood event with the corresponding return period. This is also the case for the risk calculation without measures.
- **Land use**
  In most areas, the land use is different per location. Like described in Section 3.1, the land use map is an essential part of the economic flood risk calculation.
- **Damage functions**
  The damage functions relate the inundation depth to the economic damage and are also part of the risk calculation without measures. Damage functions are in the form of a table.
- **Cost data**
  Each measure leads to different costs. The investment cost as well as the operation and maintenance cost are different per adaptation measure and can vary depending on the design return period of the measure. In addition, the standard deviations of the cost components can be given for the uncertainty analysis. The cost indications are in table form and need to be checked when applying the framework in a new area.
- **Input variables**
  Other than the above mentioned elements, additional input variables are required for the calculations. The variables are in table form and contain e.g. the considered time horizon, discount rate and indirect damage factor.

With the above described input, the calculations can be performed. These calculations are done for each measure variant. Each variant contains a first measure, an optional corresponding protection level and an optional second measure (without specified protection level). So, single measures can be measures with or without a design protection level. Combinations of two measures contain one measure with a protection level and one measure without a protection level. The starting point of each calculation is the base situation without any applied adaptation measures. This situation is equal to the already performed base risk calculation, with investment and operation and maintenance costs equal to zero. Thereafter, the measure variant is applied. The measures can have effect on the return periods, inundations, land use and damage functions. Also, the measures increase the investment and yearly operation and maintenance cost. This is further elaborated in Section 3.3 and 3.4. For measure combinations, the second measure is applied to the earlier modified return periods, inundations, land use and damage functions. After the modifications, the risk can be calculated in the same way as in the base situation (see Section 3.1). The cost is calculated with the investment and operation and maintenance costs. This is expressed in the present value, considering the entire time horizon. The cost calculation is as follows:

$$PV_{\text{cost}} = I + \sum_{t=1}^{T} \frac{OM}{(1+r)^t} \tag{3.5}$$

Where:

PV_{cost} [€] = Present value of the measure cost
I [€] = Investment cost of the measure
OM [€/year] = Operation and maintenance cost of the measure
T [years] = Time horizon
r [-] = Discount rate

With the found flood risk and cost, the key performance indicators can be calculated. These are the total costs (TC), net present value (NPV), internal rate of return (IRR) and the benefit-cost ratio (BCR). The calculation of the total costs is as follows:

$$TC = PV_{\text{risk}} + PV_{\text{cost}} \tag{3.6}$$

Where:

TC [€] = Total costs when the measure is applied
PV_{risk} [€] = Economic risk when the measure is applied (see Equation (3.4))

Secondly, the net present value shows the absolute difference between the benefit and cost considered the entire time horizon. It is calculated as follows:

$$NPV = PV_{\text{benefit}} - PV_{\text{cost}} = \left(PV_{\text{risk,0}} - PV_{\text{risk}}\right) - PV_{\text{cost}} \tag{3.7}$$

Where:

NPV [€] = Net present value when the measure is applied
$PV_{\text{risk,0}}$ [€] = Economic risk in the base scenario

The third key performance indicator, which is the internal rate of return, gives the discount rate r for which the net present value results to 0. The equation to find this performance indicator is shown below and is based on Equations (3.4), (3.5), (3.6) and (3.7). The solution for the IRR can be found numerically.

$$-I + \sum_{t=1}^{T} \frac{ARR - OM}{(1+IRR)^t} = 0 \tag{3.8}$$

Where:

ARR [€/year] = Annual risk reduction, $ARR = AAD_0 - AAD$
IRR [-] = Internal rate of return

Finally, the benefit-cost ratio gives the relative difference between benefits and costs and can be calculated as follows:

$$BCR = \frac{PV_{\text{benefit}}}{PV_{\text{cost}}} = \frac{PV_{\text{risk,0}} - PV_{\text{risk}}}{PV_{\text{cost}}} \tag{3.9}$$

Where:

BCR [-] = Benefit-cost ratio when the measure is applied

The results from the calculation of the risk, cost and key performance indicators are used to produce the output. This output contains seven elements. More information about the output for the example area can be found in Section 3.6. The output elements are as follows:

- **Risk maps**
  These are the maps that contain the residual flood risk per measure strategy. The number of maps is equal to the number of measure variants plus one risk map without any measures applied. The layout of these maps is similar to the input risk map without any measures.

- **Damage graphs**
  The damage graphs show the economic direct damage against the flood probability per measure strategy. These graphs give more insight into the risk reduction per strategy, as the area below these graphs represents the flood risk. The number of damage graphs is equal to the number of measure variants plus one damage graph without applied measures.

- **Cost graphs**
  The cost graphs are meant for comparing the different variants per adaptation measure. Per design protection level, the cost, residual risk and total cost are plotted. With this, the variant with the lowest total costs is illustrated. These graphs are based on the method from Van Dantzig (1956). The number of graphs is equal to the number of unique measure combinations.

- **Net present value graph**
  In this graph, the net present value results are shown from the uncertainty calculation. The results are confidence intervals per measure variant. In Section 3.5 the uncertainty analysis within the framework is described more in detail. If the uncertainty analysis is not performed, the net present value results are shown in a bar graph.

- **Quantity table**
  The required measure quantities per measure strategy can be found in the quantity table. This table also contains the investment and yearly operation and maintenance cost, as well as the yearly remaining risk (AAD).

- **Results table**
  Results from the calculations are displayed in the results table. It contains the cost, risk reduction and key performance indicators summed up over the area for the base scenario and each adaptation measure variant. The variants are ranked based on the benefit-cost ratio.

- **Background information**
  Lastly, there is background information that is meant for a better understanding of the framework's calculations. In the background information, the input inundation maps, land use and damage functions can be viewed. In addition, the extents of the measures are given that are used for the determination of the measure quantities and cost.

3.3. Measure risk effects

In this section, the flood adaptation measures that are in the framework are described. Per measure, the risk effects are given. The determination of the measure risk effects as well as the implementation of the measures in the framework were part of this thesis. The measures are grouped into three categories, these are non-structural adaptation (Subsection 3.3.1), structural adaptation (Subsection 3.3.2) and nature-based solutions (Subsection 3.3.3). Non-structural measures are related to preparedness activities and policy. Structural adaptation involves (grey) infrastructure projects. Nature-based solutions are changes in the landscape and also have possible environmental benefits. The adaptation measures either reduce the flood probability or the consequence. Probability reducing measures have effect on the inundation maps, while consequence reducing measures affect the damage functions. Furthermore, the measures can have effect on coastal, fluvial and/or pluvial flooding areas. Table 3.1 shows all the measures in the framework.

Table 3.1: Flood adaptation measures in the framework. The measures are categorized by measure type, reduction type and effect on coastal, fluvial and pluvial flooding.

Measure type	Measure	Reduction	Coastal	Fluvial	Pluvial
Non-structural adaptation	Spatial relocation	Consequence	🟦	🟦	🟦
	Early warning system	Consequence	🟦	🟦	🟦
Structural adaptation	Levee system	Probability	🟦	🟦	
	Landfill	Probability	🟦	🟦	
	Water retention	Probability		🟦	🟦
	Temporary barrier	Probability	🟦	🟦	
	Dry proofing	Consequence	🟦	🟦	🟦
	Wet proofing	Consequence	🟦	🟦	🟦
	Elevating buildings	Consequence	🟦	🟦	🟦
Nature-based solutions	Delay rainwater runoff	Probability			🟦
	Living shoreline	Probability	🟦		

3.3.1. Non-structural adaptation

In this subsection, the non-structural adaptation measures are explained. Non-structural adaptation involves preparedness activities in terms of forecasting and emergency response. Two non-structural measures are in the framework: spatial relocation and an early warning system.

Spatial relocation

Figure 3.8: Overview of a spatial redesign measure

A relocation of facilities in the selected region has impact on the damages from floods (Figure 3.8). Relocation as a measure against floods involves changing the land use of the area. A different land use leads to a different areal value. This value is also the maximum damage that can occur. If the land use is changed such that the value of the area decreases, the damages decrease as well. In terms of damage functions, this means that the initial function is changed to the function of the new land use. The land value and therefore the maximum damage changes as well. The area that needs to be relocated is the flooded area for the design return period (protection level). The most extreme variant of this measure is a strategic retreat. In that case, the value of the area is reduced to zero. This is visualised in Figure 3.9. Removing the development by relocating can be achieved by buyouts: governments obtain the real estates by buying from the owners and leave the area open. Although the effectiveness of a relocation measure is maximum, this method is expensive (New York City Department of City Planning, 2013).

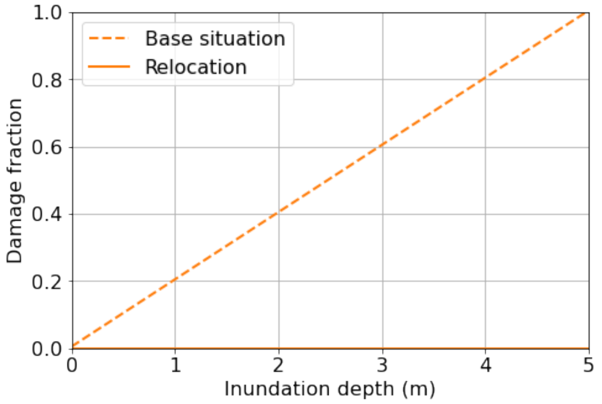


Figure 3.9: Effect of the relocation on the damage function

Early warning system

Figure 3.10: Overview of an early warning system measure

Once a flood event occurs, an early warning system in combination with a good evacuation plan reduces the damages from the flood event (Figure 3.10). Not only affected people but also their valuable belongings can be moved to safer areas or higher elevations. This leads to a milder damage curve, because part of the value can be kept away from the flood effects. This part depends on the time between the warning and the flood event. The Day's curve, developed by Harold Day in the 1960s, relates the forecast lead time to the percentage of damage reduction. This curve was adjusted by the New York district (Scawthorn et al., 2006). According to this relation, the damage reduction is 23 % if the lead warning time is 12 hours. If the lead time is longer than 24 hours, the damage reduction can be up to 35 %. The effect for a 12 hour lead time is shown in Figure 3.11. This measure does not have any variants based on the protection level in the framework. However, it can be combined with other measures that have a design protection level.

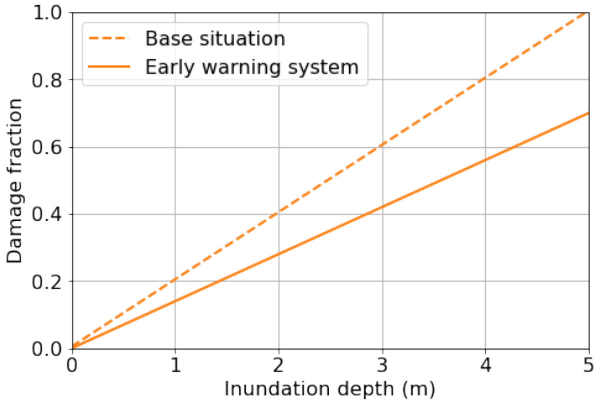


Figure 3.11: Effect of the early warning system on the damage function

3.3.2. Structural adaptation

This subsection presents the structural adaptation measures. Measures of this type are ’hard’ measures, because it involves a structure or a change to an existing structure. The framework contains seven structural measures: levee system, landfill, water retention, temporary barrier, dry proofing, wet proofing and elevating buildings.

Levee system

Figure 3.12: Overview of a levee system measure

With this measure, a levee ring is constructed around the selected measure region (Figure 3.12). The levee height depends on the design return period (protection level). To prevent the effects of a certain flood scenario, the levee height should be higher than the inundation depths around the measure region. Since the levee system has no effect for higher water levels, more extreme flood scenarios are considered in the same way as without this measure. The effect on the inundation depths is shown in Figure 3.13.

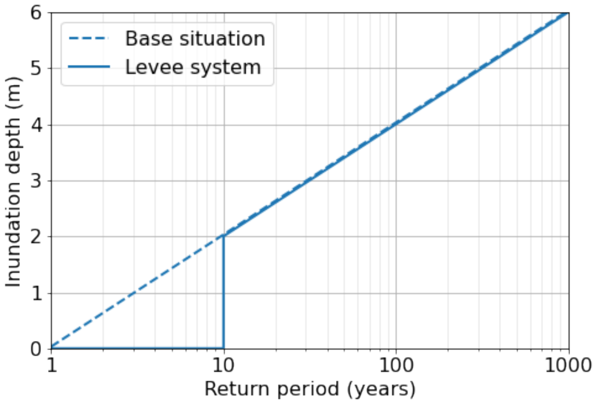


Figure 3.13: Effect of the levee system on the inundation depth curve

Landfill

Figure 3.14: Overview of a landfill measure

The landfill measure affects the land elevation of the selected region: this is heightened up to a design land elevation (Figure 3.14). This elevation depends on the protection level. Inundation depths for the design flood scenario should be minimized by the new land elevation. A higher land elevation means that all inundation depths are lowered by the elevation increase. The effect on the inundation depths is shown in Figure 3.15. Implementation of a landfill may lead to relocation of current activities in the region (New York City Department of City Planning, 2013). Such effects are not considered in the framework.

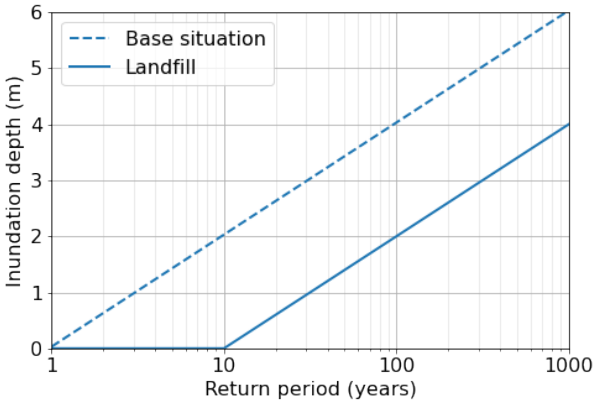


Figure 3.15: Effect of the landfill on the inundation depth curve

Water retention

Figure 3.16: Overview of a water retention measure

The discharge and storage of surplus water volume elsewhere is a measure that is especially convenient for areas that could be affected by fluvial or pluvial floods (Figure 3.16). This measure can be realized by installing a drainage system in the form of canals and sewage. In addition, space is required for the storage of water until the extreme rainfall or river discharge event is over. This retention area can be for instance a polder (New York City Department of City Planning, 2013). Because the inundation maps do not contain information about the time lapse of the floods, the effect of this measure is deducted from the storage capacity of the polder. The storage capacity depends on the design return period (protection level) and is the potential volume that can be drained from the flooded area. The drainage system that transports the water to the retention area has a limited discharge capacity. Therefore, the storage capacity of the polder is only reached when the drained water is evenly distributed over the area. In case of large differences in inundation depths over the area, this measure is less efficient. The decrease in inundation is equal to the storage capacity of the polder divided by the surface of the flooded area. This leads to the graph shown in Figure 3.17. Because the framework accounts for water retention in a simple form, it is important to perform more detailed simulations when this measure is found to be appropriate.

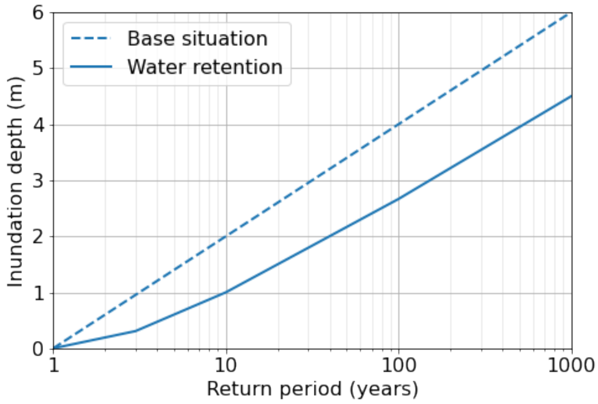


Figure 3.17: Effect of the water retention on the inundation depth curve

Temporary barrier

Figure 3.18: Overview of a temporary barrier measure

Figure 3.19: Sand bags are an example of temporary barriers (source: HESCO, 2016)

If the flood can be predicted on beforehand, temporary measures could be made such as temporary flood barriers (Figure 3.18). Temporary barriers are effective up to a limited height as the barriers must be stored and installed. These are not visible in normal situations (New York City Department of City Planning, 2013). A typical height for a temporary barrier is 1 m (HESCO, 2016). The maximum height of the temporary barrier is an adjustable variable in the framework. An example of temporary barriers is sand bags, as shown in Figure 3.19. Due to a detection, placement or construction failure in the temporary barriers, there is a considerable failure probability compared to permanent structures (Lendering et al., 2014). The effect on the inundation is shown in Figure 3.20. This effect is the same as for a permanent levee system if the temporary barrier does not fail. Like the levee system, temporary barriers could be designed for different protection levels, provided that the maximum height is not exceeded.

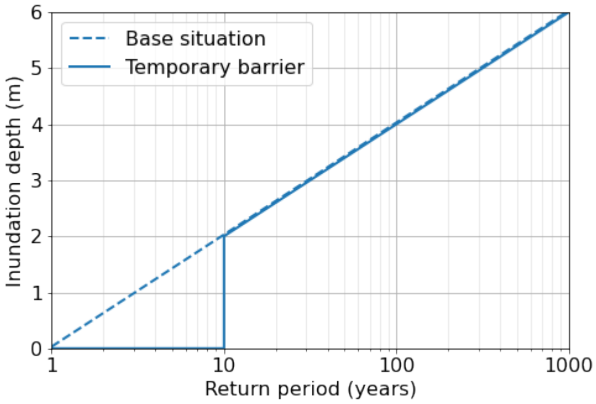


Figure 3.20: Effect of the temporary barrier on the inundation curve

Dry proofing

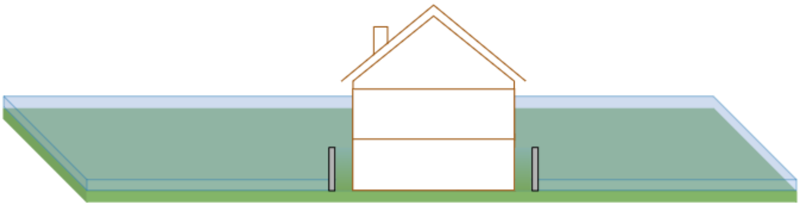


Figure 3.21: Overview of a dry proofing measure

Figure 3.22: Practical example of a local flood wall, which is a form of dry proofing (source: Flood Control International, 2020)

This technique is aimed to reduce damages on buildings within a flooded area (Figure 3.21). By means of panels, coatings, sealed doors and windows or flood walls around the building (New York City Department of City Planning, 2013), floods decreased effect on the damages on and within the building. In the framework, dry proofing is schematized by flood walls around buildings (Figure 3.22). These flood walls are designed for flood depths up to 1.5 m (FEMA, 2013). Lower dry proofing walls could also be chosen, based on the inundation depth at the location for the design return period. Like the levee system, there is no damage to the building for inundation depths lower than the wall height. Larger depths result in the same damage as without the dry proofing. This effect is shown in Figure 3.23. Dry proofing can only be applied on buildings, which means certain land uses.

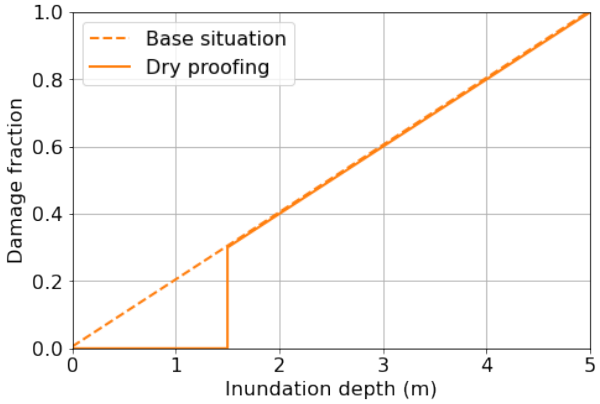


Figure 3.23: Effect of the dry proofing on the damage function

Wet proofing

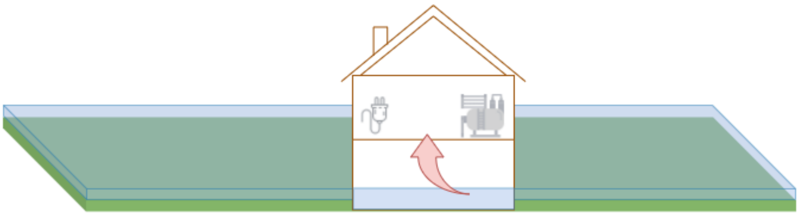


Figure 3.24: Overview of a wet proofing measure

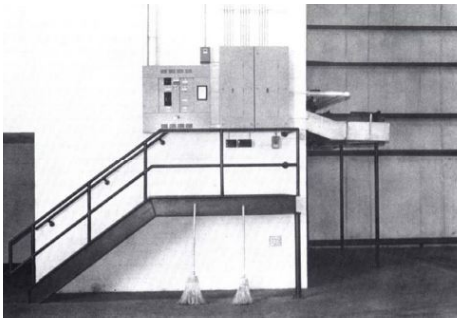


Figure 3.25: Elevating the electrical utilities is an example of wet proofing (source: FEMA, 2007)

Changing the buildings by means of wet proofing can be an effective way to deal with the consequences of flood scenarios (Figure 3.24). The principle of wet proofing is to create a space at the bottom of buildings that allow water to flow in (New York City Department of City Planning, 2013). This space can be created by moving expensive building content to a higher elevation (De Moel et al., 2014). Figure 3.25 shows an example of this. By allowing water in buildings, the hydrostatic pressures on buildings are reduced. However, only part of the damages can be reduced. De Moel et al. (2014) stated that wet proofing reduces the damages on buildings with about 40 %. The suggestion is that wet proofing could be effective for inundation depths up to 3 m, when the flood also reaches higher floors. However, the wet proofing height can be variable. For the framework, this height depends on the inundation at the location of interest for the design return period. The effect on the damage curve for an effect up to 3 m is shown in Figure 3.26. Like for dry proofing, this measure is only effective for buildings.

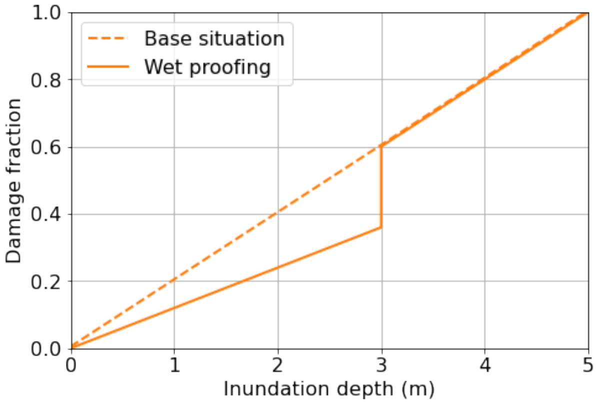


Figure 3.26: Effect of the wet proofing on the damage function for an effect on inundations up to 3 m

Elevating buildings

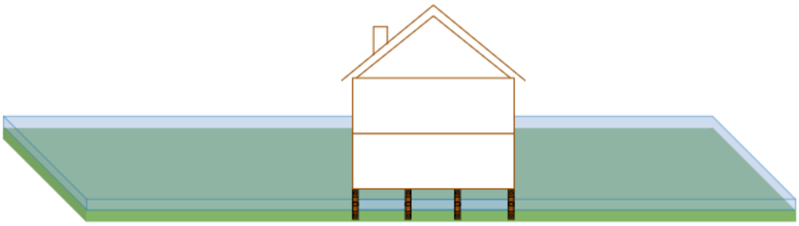


Figure 3.27: Overview of an elevating buildings measure

All effects of a flood can locally be avoided by elevating buildings. The elevation can be achieved by piles or a local landfill (New York City Department of City Planning, 2013), as shown in Figure 3.27. This local landfill is different from the landfill measure, because the fill only covers the building. Damages are only present when the inundation depth becomes higher than the design inundation depth of the building elevation. This effect on the damage curve is shown in Figure 3.28. In the figure, the building is elevated by 1 m. The elevation height depends on the inundation depth for the design protection level for the location of the building. This measure is also only applicable to building areas.

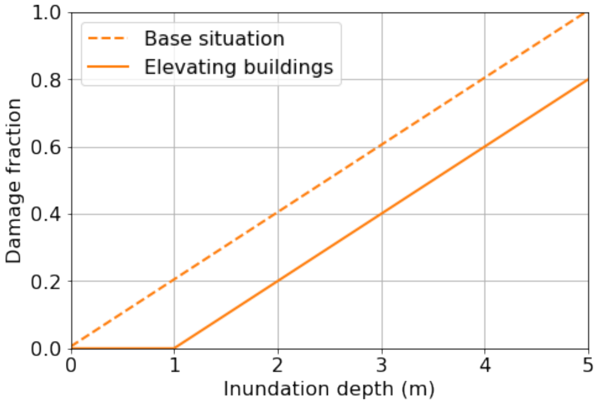


Figure 3.28: Effect of the building elevation on the damage curve

3.3.3. Nature-based solutions

This subsection is about nature-based solutions, the last measure type. These solutions are based on natural processes from the landscape. The measures are physical but 'soft'. Two nature-based measures are in the framework: delay rainwater runoff and living shoreline.

Delay rainwater runoff

Figure 3.29: Overview of a delay rainwater runoff measure

Figure 3.30: Green roofs and green spaces are examples of delaying the rainwater runoff in urban areas (source: Hendriks, 2017)

For areas that are affected by pluvial flooding, the delay of rainwater runoff during extreme rainfall events can be a solution (Figure 3.29). Delaying the runoff is achieved by changing the subsoil in urban areas. Open green spaces are able to retain part of the rainwater, making pluvial flooding less likely. Examples of this are green strips, parks and green roofs (see Figure 3.30). In the framework, the effect of delaying the rainwater runoff is determined by the SCS relation (Maidment, 1993). This relation is widely applied in hydrology and relates the rainfall water to the runoff:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{3.10}$$

Where:

Q [m] = Direct runoff from the rainfall
P [m] = Rainfall volume
I_a [m] = Initial abstraction
S [m] = Potential retention

Equation (3.10) can be rewritten based on the empirical relation between the initial abstraction and the potential retention ($I_a = 0.2S$). This leads to

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{3.11}$$

The potential retention S is often expressed in the CN (runoff curve number), which is dimensionless. The CN value can be found as follows:

$$CN = \frac{25.4}{S + 0.254} \tag{3.12}$$

The CN value depends on the soil characteristics and the present vegetation. In an urban area without any green strips, the subsoil does not store any rainwater. In this case, $CN = 100$ and $S = 0$ m. This means that Equation (3.11) reduces to $Q = P$, so the runoff Q is equal to the rainfall volume P. In practice there is still a small amount of interception (I_a), which is neglected here. For open areas like parks, the CN value lies between 40 and 80. The assumed value for CN with a rainwater runoff delay measure is therefore 60. This leads to a potential retention of $S = 0.17$ m in the soil and a decrease in direct runoff Q. The effect is present especially for small inundation depths. Figure 3.31 shows this (exaggerated) effect on the inundation. The area of application is the flooded area for the design return period (protection level).

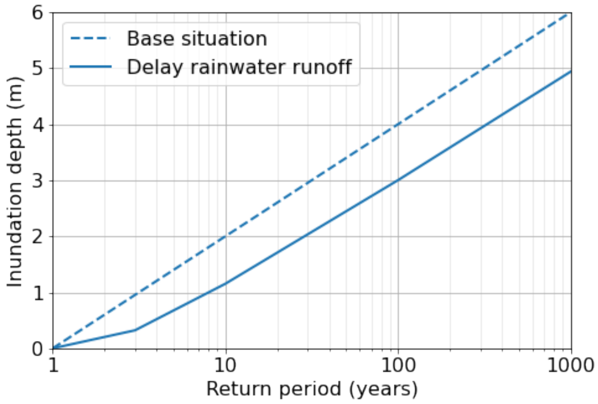


Figure 3.31: Effect of delaying the rainwater runoff on the inundation depth curve. In the plot, the initial CN value is assumed to be 100 and the new CN value is 20 (exaggeration)

Living shoreline

Figure 3.32: Overview of a living shoreline measure

The application of living shorelines is a natural solution for the reduction of inundation depths. It is applicable in areas vulnerable for coastal flooding (Figure 3.32). Living shorelines exist in many forms, examples are wetlands, salt marshes, mangrove and coral reefs. The principle of these measures is equal. Vegetation along the coast causes an increase of the bottom roughness, this leads to a reduction in wave heights and storm surge. The rate of influence of living shorelines on inundation depths depends on the wave climate, initial bottom roughness, bathymetry, width of the living shoreline and other factors. This makes a direct general relation with the inundation complex. Nevertheless, estimates were made of the change in inundation depth for a varying bottom roughness of the coast (Menéndez et al., 2018). According to these estimates, a mangrove coast with a width of 2 km results in 57 % reduction of the inundation compared to a bare sandy coast. A 1.5 km wide coral reef in front of the coast reduces the inundation by 19 %. This is in line with Zhang et al. (2012), who found a relation between the width of the mangrove and the storm surge reduction. This effect is shown in Figure 3.33, where a mangrove width of 2 km is chosen. The simple reduction as shown in the figure could lead to large errors, users of the framework should be aware of this when the results from this measure are studied. This measure does not have different variants related to a protection level. It can be combined with other measures that do have a design protection level.

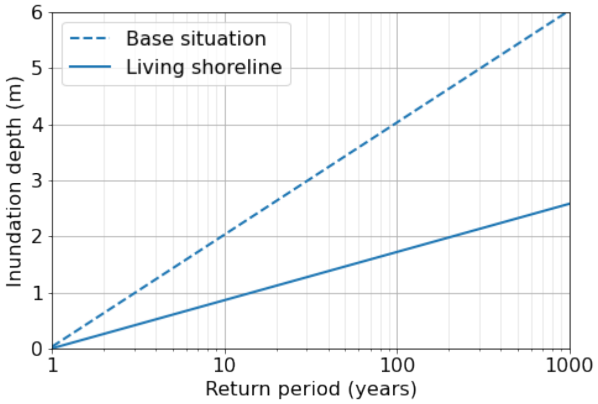


Figure 3.33: Effect of a 2 km wide mangrove coastline (living shoreline) on the inundation depth curve

3.4. Measure cost

This section contains the cost for implementing the earlier mentioned measures. Part of the cost are the initial investment and the operation and maintenance during the lifetime of the measure. The operation and maintenance cost are expressed as a percentage of the investment cost per year. Table 3.2 presents the cost per measure, where the United States is chosen as the reference country. The data is based on estimates from different reports (Aerts, 2018; Ecologic Institute and Sendzimir Foundation, 2019; Jonkman, Hillen, Nicholls, Kanning, & Van Ledden, 2013; Royal HaskoningDHV, 2020a). This data is also used for the fictional example in this chapter. The cost data is not thoroughly validated and may not be entirely correct. However, the essence here is to show the working of the framework. In practice, the user can adjust these numbers.

Table 3.2: Investment and operation and maintenance cost per adaptation measure in the framework for the United States

Measure	Investment	Unit	O&M (%)	Source
Spatial relocation	354	€/m^2	0.1	Aerts (2018)
Early warning system	17	€/ha	5.0	Royal HaskoningDHV (2020a)
Levee system	19	M€/m/km	0.2	Jonkman et al. (2013)
Landfill	25	€/m/m^2	0.2	Jonkman et al. (2013)
Retention	35	€/m^3	1.0	Aerts (2018)
Temporary barrier	5.2	M€/m/km	5.0	Aerts (2018)
Dry proofing	8.7	k€/m/building	2.0	Aerts (2018)
Wet proofing	5.3	k€/m/building	2.0	Aerts (2018)
Elevating buildings	52	k€/m/building	0.2	Aerts (2018)
Delay rainwater runoff	11	€/m^2	0.1	Ecologic Institute and Sendzimir Foundation (2019)
Living shoreline	500	€/m	3.0	Aerts (2018)

3.5. Uncertainty analysis

Because the results of the cost-benefit analysis contain uncertainty it is useful to find possible deviations of these results. This is done by an uncertainty analysis. The analysis is done for the calculation of the net present value, which is one of the key performance indicators. This performance indicator namely has a concrete unit (euros or other currency), which is not the case for the internal rate of return and the benefit-cost ratio. Compared to the total costs, the NPV provides insight into positive and negative outcomes. Therefore, it is interesting to find a confidence interval within which the NPV is expected per measure strategy. As mentioned earlier, the NPV is calculated with Equation (3.7). A further elaborated form of this equation is as follows:

$$\text{NPV} = -I + \sum_{t=1}^{T} \frac{\beta \cdot ARR - OM_t}{(1+r)^t} \tag{3.13}$$

Where:

β [-] = Risk factor
OM_t [€] = Operation and maintenance cost in year t

For the uncertainty analysis the flood risk, investment and operation and maintenance are used as stochastic variables. For the determination of the confidence interval, a Monte Carlo simulation is done with the stochastic variables. Per sample, a value is drawn from the distribution of each stochastic variable, as described in the following paragraphs and shown in Figure 3.34.

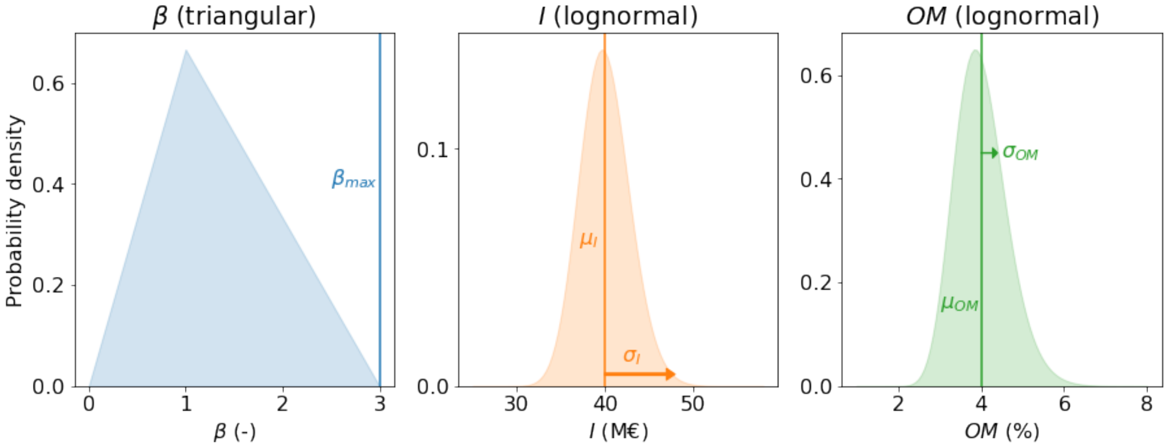


Figure 3.34: Example distributions of the considered stochastic variables β, I and OM with the adjustable parameters β_{max}, μ_I, σ_I, μ_{OM} and σ_{OM}

The flood risk, represented by the annual risk reduction ARR (the benefit of the measure) in Equation (3.13), is related to two variables. Namely, the annual risk reduction follows from $ARR = AAD_0 - AAD$, where AAD_0 is the expected yearly damage in the initial situation without measures. AAD is calculated with the measure changes on the inundation, land use and the damage functions. The uncertainty in the flood risk, which is mainly caused by uncertainties in the inundation maps and damage functions, is included in both AAD_0 and AAD. Therefore, a factor β is included in Equation (3.13) for the risk term ARR. This factor has a triangular distribution. The minimum is set to 0, because the risk is always positive. The mode is set to 1, because the calculated deterministic risk should have the highest probability of occurrence. The maximum (β_{max}) can be adjusted (Figure 3.34). The higher the maximum is chosen, the larger the uncertainty of the flood risk. It is assumed that the risk does not change per year, because the flood probabilities and consequences are - apart from climate change and area development - constant over time.

The value as well as the uncertainty in investment cost can differ per measure. For example, there is detailed information about the investment for a levee system in the Netherlands. On the other hand, not so much is known about the cost for a strategic retreat (relocation). Such uncertainties can be taken into account by the user in the standard deviation of the investment σ_I (Figure 3.34). Because the investment is not expected to have negative values, the investment cost is assumed to have a lognormal distribution. The mean and standard deviation are given by the user. The investment takes place at the beginning of the considered time period and is therefore not varying over time.

For the operation and maintenance cost per year a percentage is assumed of the investment cost. This was also done previously in the deterministic calculation of the NPV, in Equation (3.7). In this way, the investment and operation and maintenance cost are dependent. This percentage is not only varying per sample but also per year of the considered time period. Especially the maintenance cost changes over time, e.g. due to repairs. Like for the investment, negative operation and maintenance costs are not expected. Therefore, a lognormal distribution is assumed for this variable (Figure 3.34).

By including the three variables mentioned in the previous paragraphs, the result still contains not considered uncertainties. These are the discount rate r and the model uncertainty. In the uncertainty study of Westerhof (2019), the variables in the economic risk calculation were ranked based on the influence on the result's uncertainty. It was concluded that the discount rate has a smaller influence than the inundation depths and damage functions (the flood risk) and the cost (investment and operation and maintenance) on the cost-benefit analysis. In addition, the discount rate is in practice a geopolitical term and is determined per project. This is done by the client (e.g. The World Bank), the beneficiary party (e.g. local authorities) or by the government (part of the policy). Therefore, the discount rate is included as a deterministic variable. The model uncertainty relates to the modifications of the inundation maps, land use and damage functions. When developing the framework, a conscious choice was made for measures with a clear effect on the flood risk. The measures do not require a hydraulic simulation, which reduces the uncertainty of the risk relative to the scenario without measures. For measures with a reduction factor, such as the early warning system, this factor is adjustable for the user. Eventual uncertainties of specific measure effects could be included by using the framework multiple times with different effect values.

In the Monte Carlo simulation, values of the above described variables are drawn for each sample. With the samples, the net present value is calculated. This results in a series of NPV realizations, with the same size as the number of samples N. This number can also be chosen by the user. With the series it is possible to determine a confidence interval. This is done with the method of Tukey, in which the interval is based on the inter-quartile distance (difference between the third and first quartile of the data). The result is a boxplot, showing the confidence interval of the simulation. By putting the boxplots of different measure strategies next to each other, the uncertainties can be compared. It can also be chosen to use the framework without the uncertainty analysis. In that case, the NPV per measure strategy is shown in a bar graph instead of a boxplot graph (see Appendices A and B for a visualisation).

3.6. Example results

In this section, the output of the framework is discussed. The output is created based on the cost and risk reduction calculations of the different adaptation measures. For this section, the landfill and early warning system measures are selected within the fictional example area. The framework's menu, in which these measures are selected, is shown in Figure 3.35. Intermediate steps in the calculation are given based on the risk calculations from Section 3.1. The used variables are given in Table 3.3.

Table 3.3: Input variables for the example simulation

Symbol	Description	Value	Unit
$\Delta x, \Delta y$	Grid size	25	m
T	Time horizon	50	years
r	Discount rate	4	%
N	Number of samples (uncertainty analysis)	1000	-
IDF	Indirect damage factor	2	-
η_{ews}	Reduction effect early warning system	0.23	-

Uncertainty analysis: [✓ Yes] No

Background information: [✓ Yes] No

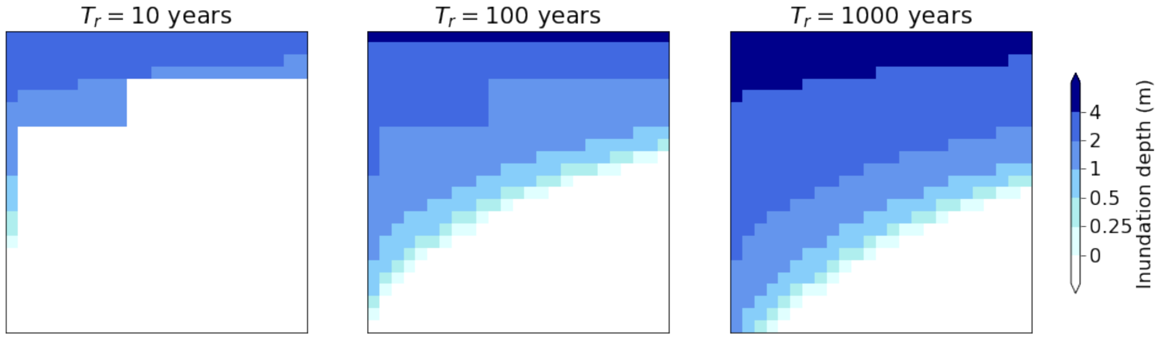
Coastal flooding

☐ Levee system
☑ Landfill
☐ Dry proofing
☐ Wet proofing
☐ Elevating
☐ Relocation
☐ Living shoreline
☑ EWS
☐ Temporary

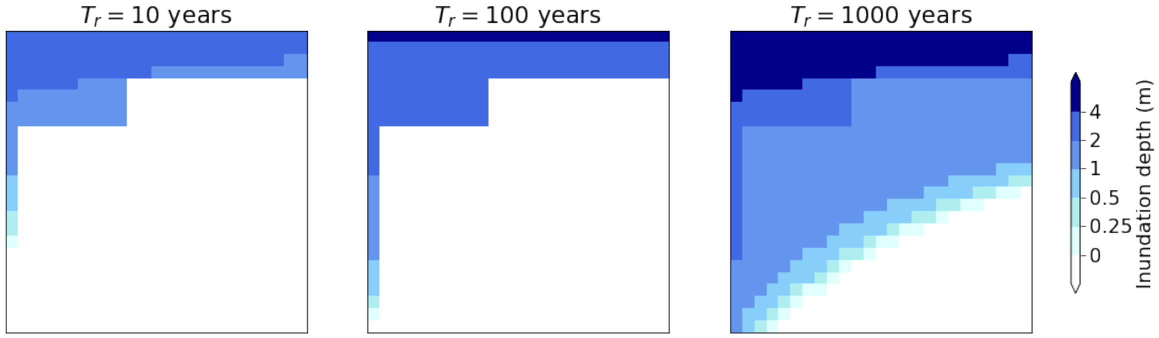
Figure 3.35: Menu of the framework with the chosen options and measures for the example simulation

When the landfill measure is applied, the inundation maps are modified. Figure 3.2 (Section 3.1) shows the initial inundation maps for the area. For the given design return period (protection level), the area is elevated such that all inundation depths are reduced to zero. For higher return periods, inundation depths are also reduced by this elevation height (see Section 3.3). For landfill protection levels of 1/10, 1/100 and 1/1,000, the modified inundation maps are shown in Figure 3.36a, 3.36b and 3.36c respectively. Note that the inundation depths are not reduced for locations with no land value.

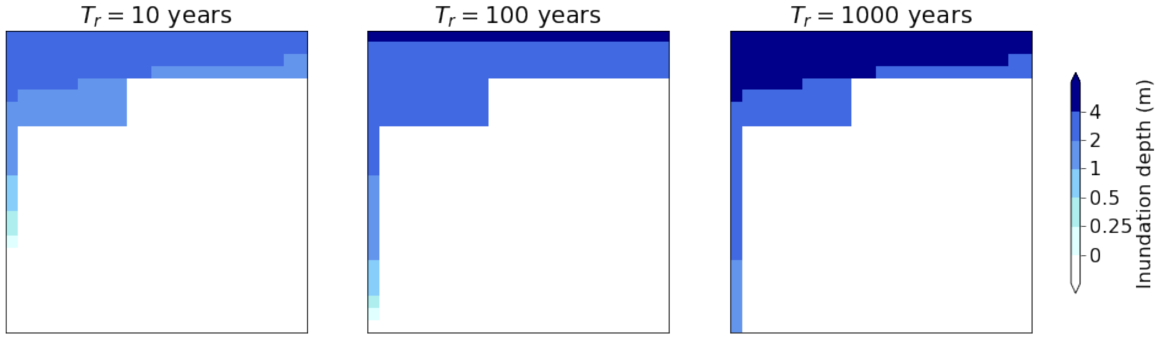
With the early warning system measure, the damage functions are modified. Figure 3.4 (Section 3.1) shows the initial damage functions for the area. Because the effect of the early warning system does not depend on a protection level, there is one possible effect for this measure in this area. However, this measure can be combined with the landfill measure. With the early warning system, the damage functions are multiplied by a reduction factor of 0.77 (see Section 3.3). Figure 3.37 shows the modified damage functions.



(a) Modified inundation maps for a landfill measure with a protection level of 1/10



(b) Modified inundation maps for a landfill measure with a protection level of 1/100



(c) Modified inundation maps for a landfill measure with a protection level of 1/1000

Figure 3.36: Modified inundation maps for a landfill measure with different protection levels

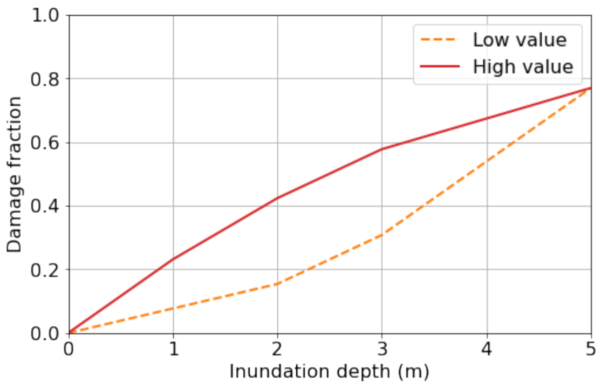


Figure 3.37: Modified damage functions for an early warning system measure

Because the landfill and early warning system measures can also be applied simultaneously, these measures lead to several measure strategies. These strategies are as follows:

0. Do nothing
1. Landfill (protection level 1/10)
2. Landfill (protection level 1/10) in combination with early warning system
3. Landfill (protection level 1/100)
4. Landfill (protection level 1/100) in combination with early warning system
5. Landfill (protection level 1/1,000)
6. Landfill (protection level 1/1,000) in combination with early warning system
7. Early warning system

Depending on the measure strategy, a different set of inundation maps and damage functions is used in the damage calculation. The resulting damage maps lead to one risk map per strategy. From the yearly risk map, the present value of the risk is calculated with Equation (3.4). Apart from the risk calculation, the measure costs are determined. The costs consist of one-time investment costs and yearly operation and maintenance costs. Those are calculated by using the values from Table 3.2 and the measure quantities. The present value of the cost is calculated from the investment and operation and maintenance by Equation (3.5).

For the uncertainty analysis, some additional parameters must be chosen. These parameters can be found in Table 3.4. The risk factor β is hard to estimate, because the uncertainty of the deterministic risk calculation is not known. However, the deviation of β can be estimated by reviewing the calculated total economic damage. In the calculation of AAD (Equation (3.3)), it is assumed that the damage corresponding to the highest return period is the maximum possible damage in the area. This means that this maximum damage should be close to the economic value of the area. The relative difference between the economic value and the maximum total damage indicates the extent to which the total damages could be underestimated (Figure 3.38). Because the damage cannot be higher than the economic value of the area, the value for β_{max} can be calculated as follows:

$$\beta_{max} = \frac{\text{Economic value}}{D_{tot,max}} \tag{3.14}$$

The economic value can be found by e.g. multiplying the GDP per capita country rate with the population of the area. Assuming that the example area is in the United States, the GDP per capita is €$56 \cdot 10^3$ (The World Bank, 2019). With a population of 1,500, the total economic value of the example area is estimated at 84 M€. From Figure 3.38, the maximum total damage (for $T_r = 1,000$ years) is 69 M€. Therefore, using Equation 3.14, $\beta_{max} = 1.2$.

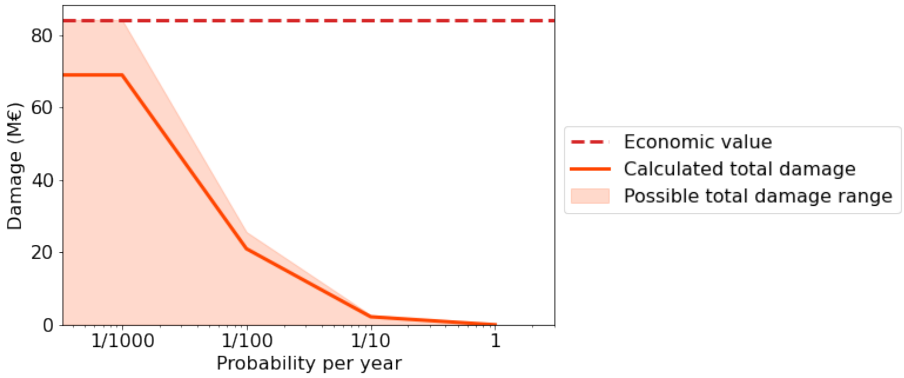


Figure 3.38: Range of damage per probability given the economic value of the example area

Data is required for the determination of the standard deviation of the investment and operation and maintenance, that contains estimates of these variables. The estimates can be obtained via reference projects or by expert judgement. The mean of the data can then be calculated as follows:

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{3.15}$$

Where:

μ [-] = Mean of the data
N [-] = Number of samples

With the mean, the standard deviation of the data can be calculated as follows:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \tag{3.16}$$

Where:

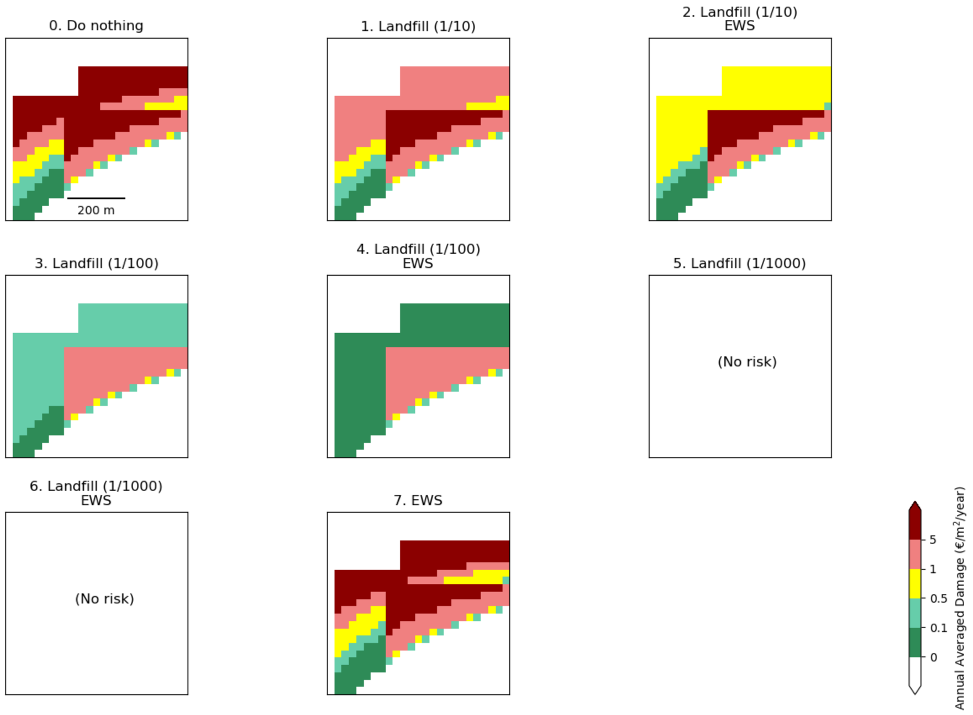
σ [-] = Standard deviation of the data

For the example, the assumed standard deviations for the investment and operation and maintenance of the two applied measures can be found in Table 3.4.

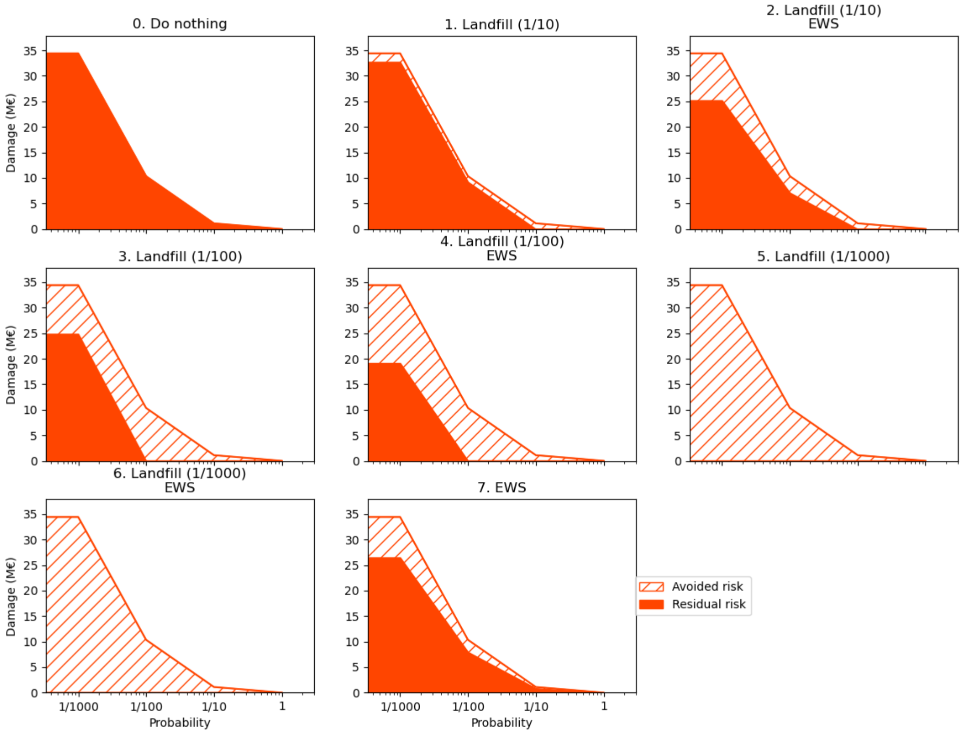
Table 3.4: Distribution parameters for the example simulation. The explanations of the parameters can be found in Section 3.5.

Measure	Symbol	Value	Unit
	β_{max}	1.2	-
Landfill	μ_I	25	€/m^2
	σ_I	5	€/m^2
	μ_{OM}	0.2	%
	σ_{OM}	0.02	%
EWS	μ_I	17	€/ha
	σ_I	3	€/ha
	μ_{OM}	5.0	%
	σ_{OM}	0.5	%

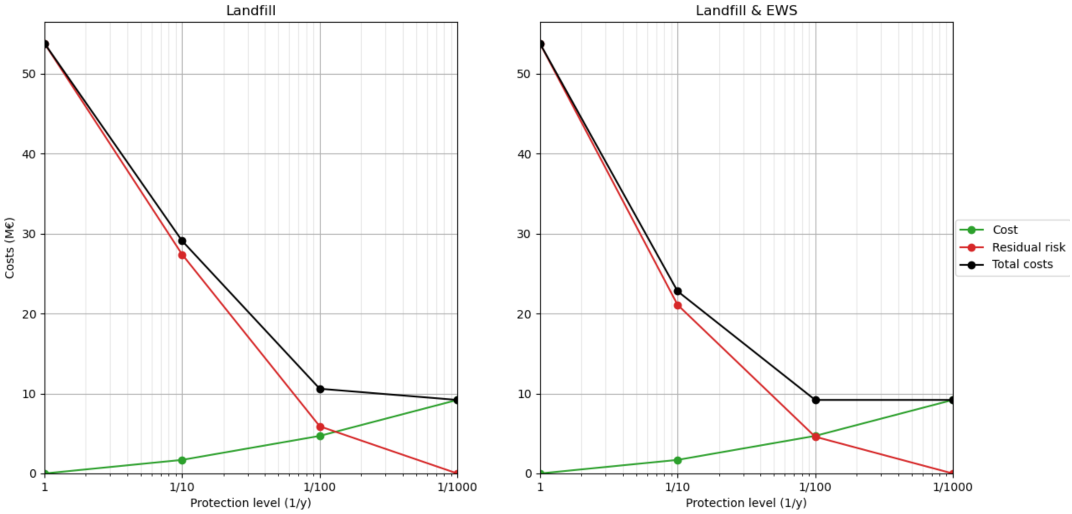
With the calculated risk, the risk reduction maps can be created. For the cost graphs and the table, the present values of the risk and cost are used. The key performance indicators are also calculated from the present values of the risk and cost (Equations (3.6), (3.7), (3.8) and (3.9)). Figures 3.39a, 3.39b, 3.39c, 3.39d, 3.39e and 3.39f show the results of the framework for the example area. The background information is shown in Figures 3.39g and 3.39h. It can be observed that the output consists of the mentioned seven elements: risk reduction maps, damage graphs, cost graphs, net present value estimations, a quantity table, a results table and background information. Those elements were also described in Section 3.2.



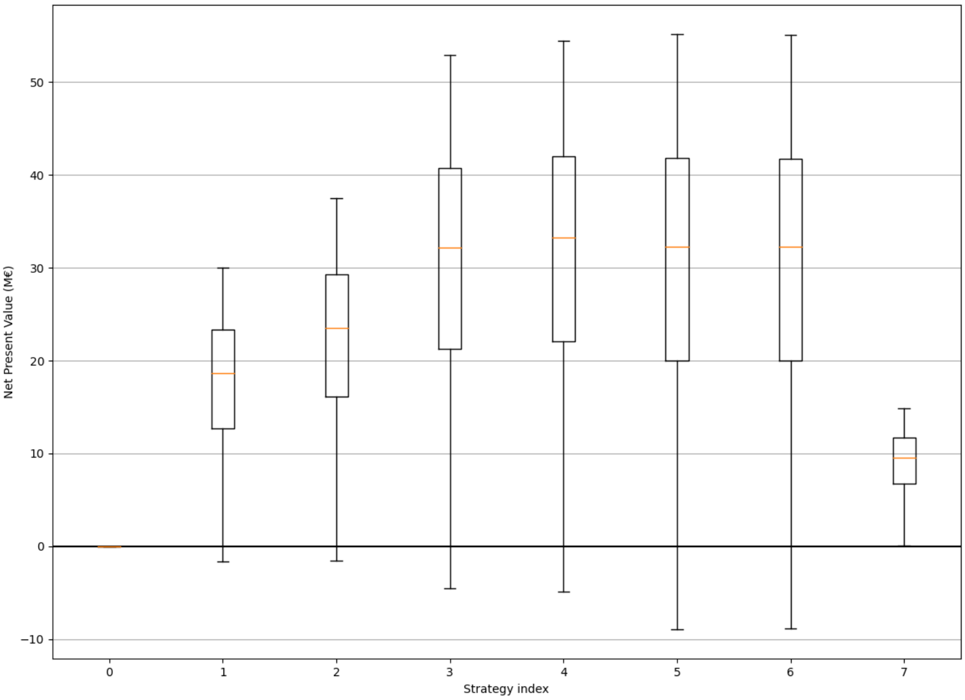
(a) Residual risk maps per measure strategy



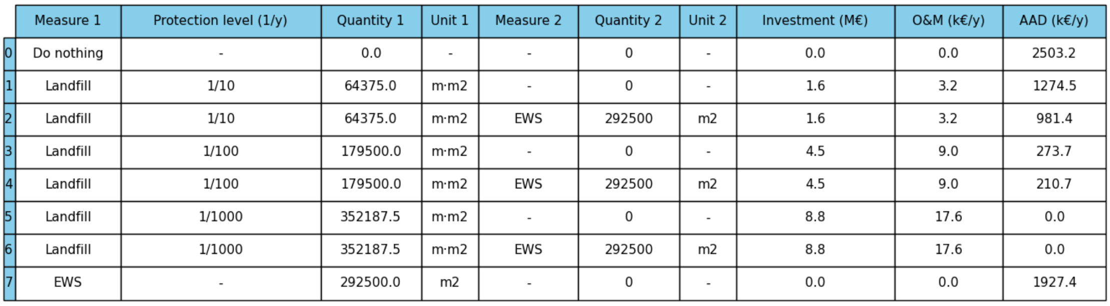
(b) Damage graphs per measure strategy. On the horizontal axis is the probability per year and on the vertical axis is the direct economic damage.



(c) Cost graphs per measure. On the horizontal axis is the design protection level and on the vertical axis is the cost.

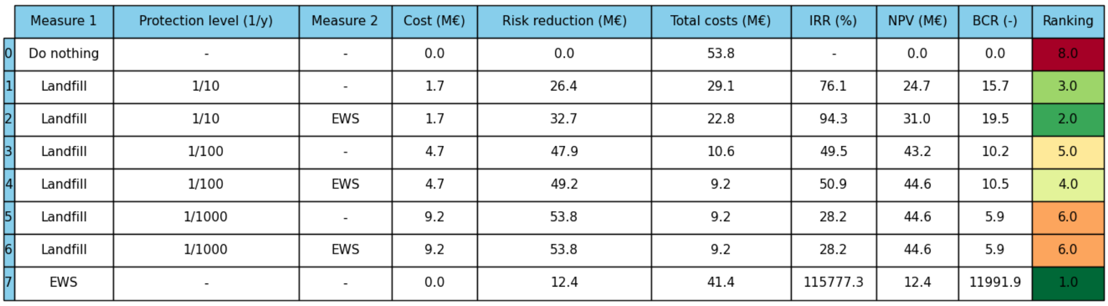


(d) Net present value graph. On the horizontal axis is the strategy index and on the vertical axis is the net present value.



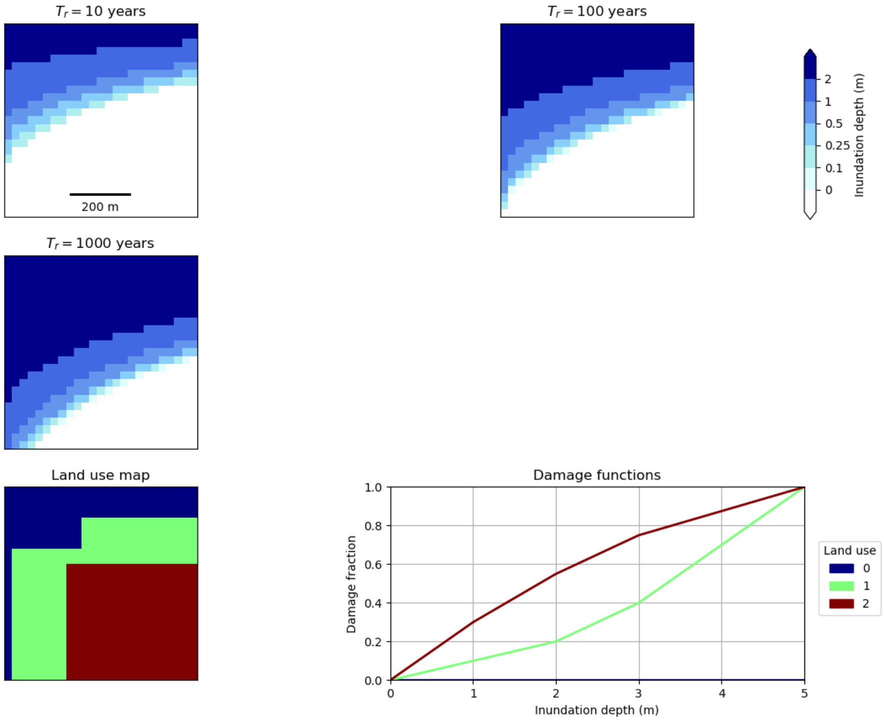
	Measure 1	Protection level (1/y)	Quantity 1	Unit 1	Measure 2	Quantity 2	Unit 2	Investment (M€)	O&M (k€/y)	AAD (k€/y)
0	Do nothing	-	0.0	-	-	0	-	0.0	0.0	2503.2
1	Landfill	1/10	64375.0	m·m2	-	0	-	1.6	3.2	1274.5
2	Landfill	1/10	64375.0	m·m2	EWS	292500	m2	1.6	3.2	981.4
3	Landfill	1/100	179500.0	m·m2	-	0	-	4.5	9.0	273.7
4	Landfill	1/100	179500.0	m·m2	EWS	292500	m2	4.5	9.0	210.7
5	Landfill	1/1000	352187.5	m·m2	-	0	-	8.8	17.6	0.0
6	Landfill	1/1000	352187.5	m·m2	EWS	292500	m2	8.8	17.6	0.0
7	EWS	-	292500.0	m2	-	0	-	0.0	0.0	1927.4

(e) Quantities and yearly cost/risk per measure strategy

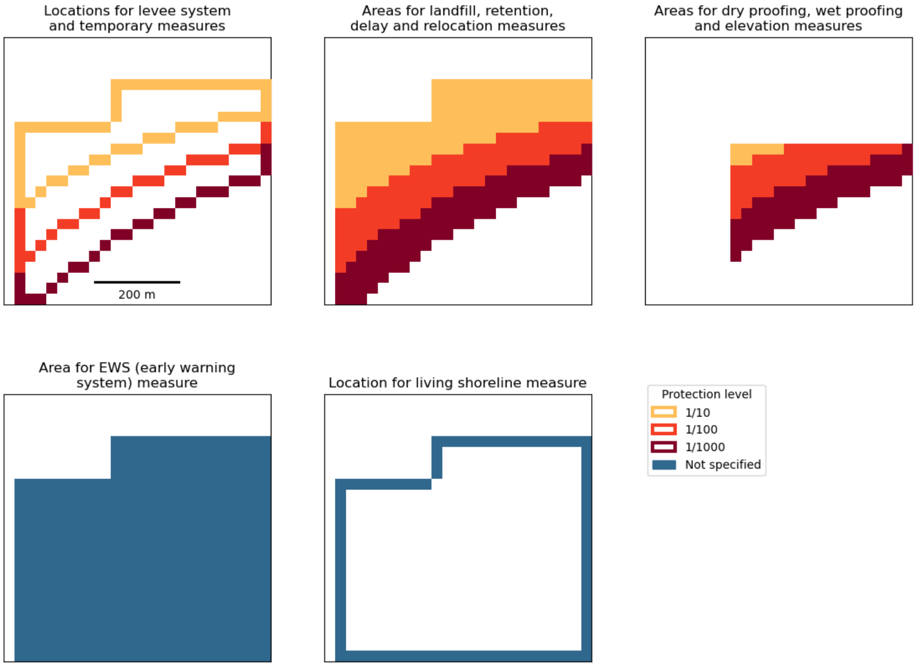


	Measure 1	Protection level (1/y)	Measure 2	Cost (M€)	Risk reduction (M€)	Total costs (M€)	IRR (%)	NPV (M€)	BCR (-)	Ranking
0	Do nothing	-	-	0.0	0.0	53.8	-	0.0	0.0	8.0
1	Landfill	1/10	-	1.7	26.4	29.1	76.1	24.7	15.7	3.0
2	Landfill	1/10	EWS	1.7	32.7	22.8	94.3	31.0	19.5	2.0
3	Landfill	1/100	-	4.7	47.9	10.6	49.5	43.2	10.2	5.0
4	Landfill	1/100	EWS	4.7	49.2	9.2	50.9	44.6	10.5	4.0
5	Landfill	1/1000	-	9.2	53.8	9.2	28.2	44.6	5.9	6.0
6	Landfill	1/1000	EWS	9.2	53.8	9.2	28.2	44.6	5.9	6.0
7	EWS	-	-	0.0	12.4	41.4	115777.3	12.4	11991.9	1.0

(f) Calculation results per measure strategy



(g) Overview of the input (inundation maps, land use map and damage functions)



(h) Extents of the measures in the area

Figure 3.39: Output framework for the example fictional area for a landfill with three different design protection levels and an early warning system

According to the maps, shown in Figure 3.39a, the spatial effect of a landfill and a combination of landfill and early warning system are comparable per protection level. The effect for protection level of 1/10 years is clearly lower than for 1/100 years and for a protection level of 1/1,000 years the risk is reduced to zero in the entire area.

The damage graphs, which are shown in Figure 3.39b, demonstrate that the landfill can reduce both the probability and the consequence, because the solid area under the graph is reduced both horizontally and vertically. The early warning system only reduces the consequence (vertical reduction of the solid area) and is less effective. All the risk is avoided for strategies 5 and 6, which was also the case in the risk maps.

In Figure 3.39c, the graphs present the optimal protection level per measure in terms of total costs. For the single landfill, this is 1/1,000 years. On the other side, the optimal protection level for a combination of a landfill and early warning system can be 1/100 and 1/1,000 years.

The total costs are not the only performance indicator. Figure 3.39d shows the confidence interval estimations of the net present value. The numbers on the horizontal axis represent the measure strategy indices. Measure strategies 3, 4, 5 and 6 all result in about the same, maximum observed NPV. However, the other strategies have smaller confidence intervals. If certainty is more important than the expected outcomes in the decision making, these strategies are more advantageous.

The measure quantities can be found in Figure 3.39e. The cost and risk calculation are based on the investment and the yearly cost and risk values from this table. Interesting is that the cost for an early warning system is very low, wherefore those are rounded to zero in the table. The reason for this is the low chosen investment cost for an early warning system (see Table 3.2).

The results table, shown in Figure 3.39f, gives the calculation results per variant. For decision making, the TC, IRR, NPV and BCR are important. The total costs of measure strategies 4, 5 and 6 are lowest.

The NPV is highest for these strategies. On the other hand, it can be observed that the single early warning system results in a very high IRR and BCR. These values seem unrealistic and are caused by the low assumed unit cost for this measure. The ranking, which is based on the BCR, therefore shows that measure strategy 7 is the best solution. If the other performance indicators are considered to be more important, one could choose for e.g. the landfill designed for 1/100 years in combination with the early warning system. This shows that the best solution does not necessarily have the best results for all the performance indicators. The outcome of the table does also correspond to the maps and graphs.

The input inundation maps, land use map and damage functions can be viewed in Figure 3.39g. This information was also presented in Section 3.1. Figure 3.39h contains the extents for not only the selected measures but also the other possible measures. For the selected measures landfill and early warning system, the extent is a certain area within the considered area. This area is different per design protection level for the landfill measure, while there is no protection level difference in case of the early warning system (see Section 3.3).

4

Case study: Phu Loc

Part of this thesis are two case studies. The first case study focuses on Vietnam, a country with a coast vulnerable to floods. The coast is eroding and typhoons can result in high storm surges. Areas along the Vietnamese coast urbanize as a consequence of increasing welfare, wherefore the damages of floods become more severe. The district Phu Loc is one of these areas (Figure 4.1). It is located at the South Chinese Sea coast, in the middle of Vietnam. The largest part of the district is rural, urban areas are found close to the coastline. Phu Loc contains two lagoons: Cau Hai in the north and Lang Co in the east. The largest lagoon, Cau Hai, has a limited connection with the sea. The three main rivers that flow through the district are the Bu Lu, Cau Hai and Truoi rivers. Phu Loc has about 141,000 inhabitants (Royal HaskoningDHV, 2020c).

Figure 4.1: Overview map of Phu Loc, Vietnam

Possible floods in the district can be caused by bad drainage during heavy rainfall events (pluvial floods), overflowing rivers due to high river discharges (fluvial floods) and high sea water levels as a consequence of tide and storm surge (coastal floods). As a result of climate change, the heavy rainfall rates are increasing and the mean sea level rises. The current flood risk measures in the district are drainage systems and levees. The levees are located on the north side of the Cau Hai lagoon. These levees are designed for fluvial floods with return periods up to 10 years (Royal HaskoningDHV, 2020c). This means that large parts of Phu Loc flood for return periods greater than 10 years. The expected flood risk is high, so new adaptation measures are required in Phu Loc.

The developed framework is applied on Phu Loc in this chapter. In Section 4.1, the input data is given. This includes the risk calculations from the existing Global Flood risk Tool. The results from the report of Royal HaskoningDHV (Royal HaskoningDHV, 2020c) are given in Section 4.2. Thereafter, in Section 4.3, the measures framework is applied. Sub-areas are selected within the district and several measures are chosen for the simulation. The results are compared with the earlier found measures from the report in Section 4.4. Lastly, a short conclusion of the case study results can be found in Section 4.5.

4.1. Input data

This section contains the input data of Phu Loc for the application of the measures framework. This includes the inundation maps (with corresponding return periods), land use map, damage functions, base flood risk map, cost data and some other variables. The flood risk map without applied measures is calculated by the existing Global Flood Risk Tool.

The inundation maps of Phu Loc are generated by MIKE, which is a 3D hydraulic model developed by DHI. Because of the safety standards in Vietnam, the inundation maps have return periods of 10, 30 and 100 years. The maps are shown in Figure 4.2.

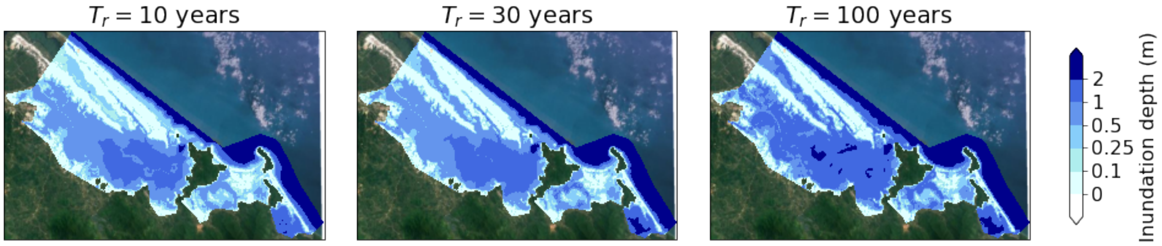


Figure 4.2: Inundation maps of Phu loc with return periods of 10, 30 and 100 years

As mentioned in Section 3.1, the land use map is important in the risk calculation. Figure 4.3 shows the land uses in Phu Loc. Note that the area where the land use is defined is not equal to the extent of the inundation maps. For locations where either the inundation depths or the land use is not visible, the damages and flood risk result to zero.

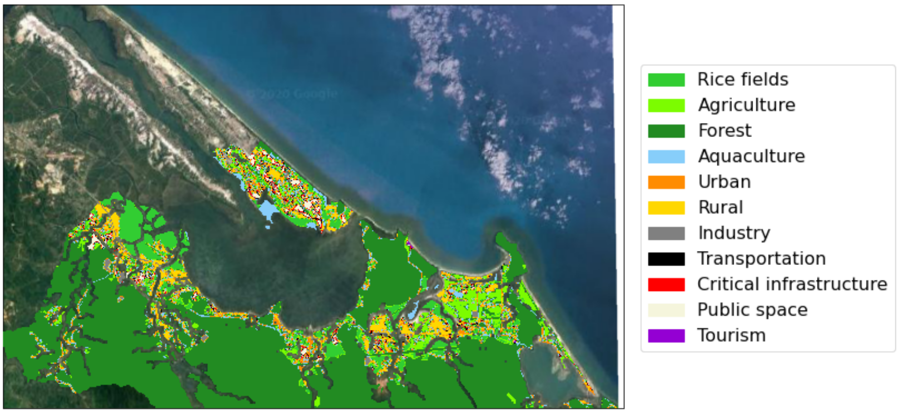


Figure 4.3: Land use map of Phu Loc

Depending on the land use, a damage function is selected to calculate the flood damage, as demonstrated in Section 3.1. The damage functions per land use are given in Figure 4.4.

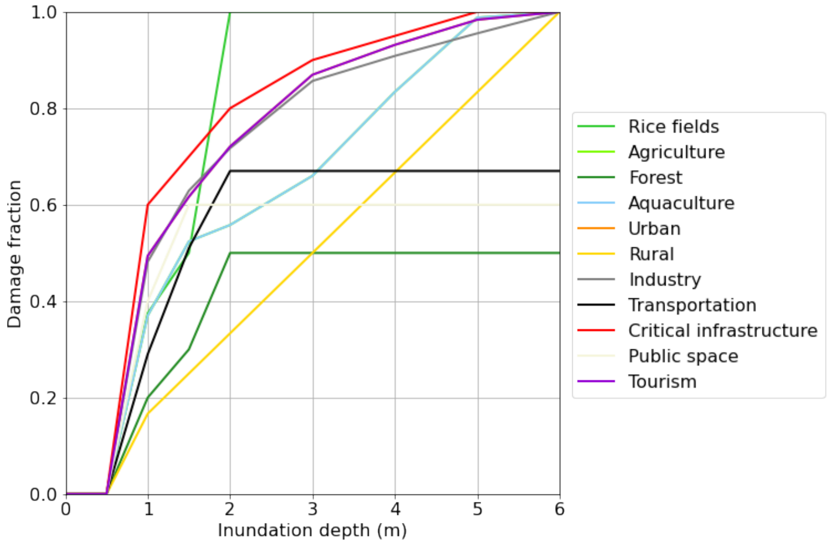


Figure 4.4: Damage functions for Phu Loc

The damage maps and current flood risk map are calculated with the existing Global Flood Risk Tool. The resulting damage maps can be found in Figure 4.5 and the risk map without any measures applied is shown in Figure 4.6. An explanation of these calculations can be found in Section 3.1.

Figure 4.5: Damage maps of Phu Loc with return periods of 10, 30 and 100 years

Figure 4.6: Risk map of Phu Loc in base situation (without any measures applied)

For the application of adaptation measures, cost data is required. Like for the fictional case (Section 3.4), the measure costs are given in the form of a table with the investment cost and operation and maintenance cost. Table 4.1 shows this information for the Vietnamese case location.

Table 4.1: Investment and operation and maintenance cost per adaptation measure in the framework for Vietnam

Measure	Investment	Unit	O&M (%)	Source
Spatial relocation	354	€/m^2	0.1	Hillen et al. (2010)
Early warning system	17	€/ha	5.0	Royal HaskoningDHV (2020a)
Levee system	1.2	M€/m/km	0.2	Jonkman et al. (2013)
Landfill	25	€/m/m^2	0.2	Jonkman et al. (2013)
Retention	23	€/m^3	1.0	Aerts (2018)
Temporary barrier	0.92	M€/m/km	5.0	Aerts (2018)
Dry proofing	541	€/m/building	2.0	Aerts (2018)
Wet proofing	251	€/m/building	2.0	Aerts (2018)
Elevating buildings	1,065	€/m/building	0.2	Aerts (2018)
Delay rainwater runoff	11	€/m^2	0.1	Ecologic Institute and Sendzimir Foundation (2019)
Living shoreline	100	€/m	3.0	Aerts (2018)

Lastly, information is required about some other input variables. These variables are important in the cost calculations and can be modified by the user. The used input variables for Phu Loc are given in Table 4.2.

Table 4.2: Input variables for the Phu Loc simulation

Symbol	Description	Value	Unit
$\Delta x, \Delta y$	Grid size	10	m
T	Time horizon	30	years
r	Discount rate	6	%
IDF	Indirect damage factor	2	-
A_{building}	Average area per building	100	m^2
h_{dp}	Maximum dry proofing height	1.5	m
η_{ews}	Reduction effect early warning system	0.23	-

The measures dry proofing, wet proofing and elevating buildings can only be applied on areas with buildings. The land uses that contain buildings are assumed to be the urban, rural, industry, critical infrastructure and tourism land uses.

The uncertainty analysis is not applied for Phu Loc. The main reason for this is the lack of measure cost data, which is necessary to determine the standard deviations. Although the standard deviations could be assumed, the resulting confidence intervals would be of a too low value considering the large remaining uncertainty in the assumptions. In addition, the results of the uncertainty analysis cannot be compared with the results from the RHDHV report. Such an analysis was not included here.

4.2. Findings analytical report

This section is about the findings from the analytical approach of Royal HaskoningDHV with respect to the screening of flood adaptation measures in Phu Loc. The initially selected measures as well as the finally chosen measures are given here.

In the report of Royal HaskoningDHV (2020c), measures are advised for Phu Loc that need to be further elaborated. This was done for 3 areas within the district (see Figure 4.7). Because the flood risk is highest in these areas, measures were selected here. The initial measure selection was made per area and was done based on logical reasoning. In Table 4.3 the initially selected measures are given per area. The table also contains measures that cannot be simulated by the framework. Important is that the levee system measure could have multiple location variants, also within these areas. Moreover, the retention measure was intended at an upstream location along the Rui river. Mangrove planting at

Figure 4.7: Areas in Phu Loc where measures are required (based on Royal HaskoningDHV, 2020c)

the lagoon banks (a living shoreline) was also considered but this was not intended for reducing flood effects. In the report it was decided on beforehand that the design protection level in Phu Loc is 1/30 years. The measures in bold in the table are the chosen measures from the report. These measures can be designed in more detail for the next stage in the decision making. Therefore, the function of the report is comparable to the function of the new framework (see Figure 2.1 from Section 2.1).

Table 4.3: Initially selected measures per area in Phu Loc with chosen measures in bold, according to Royal HaskoningDHV (2020c) (*measures that cannot be simulated by the framework)

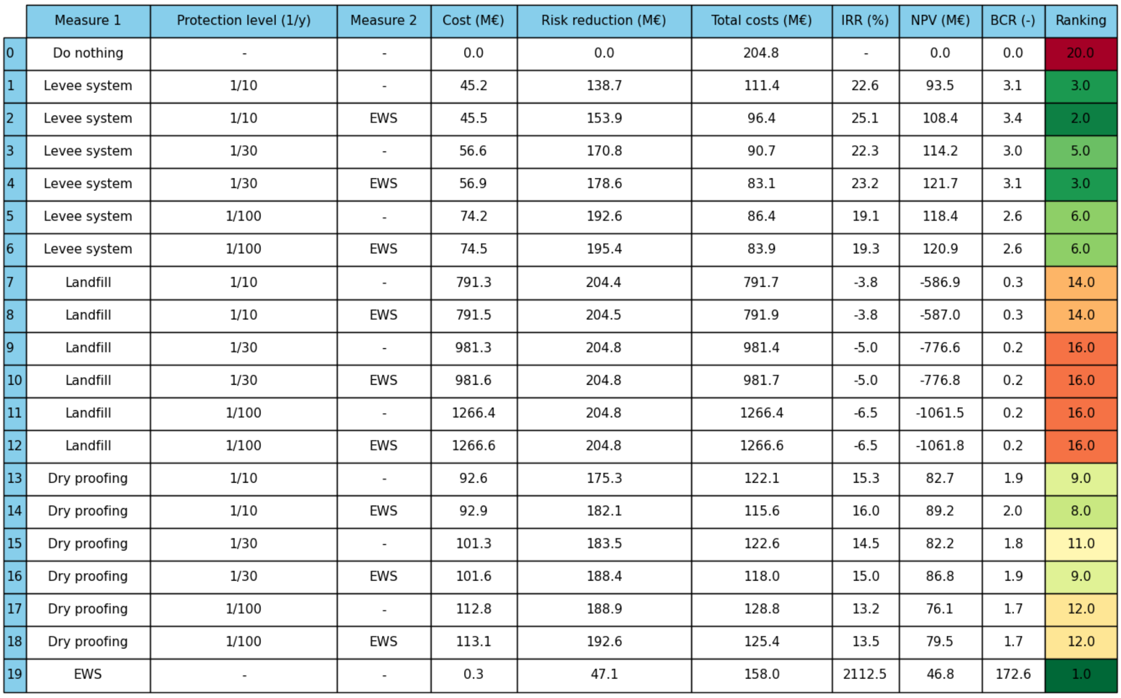
Area 1	Area 2	Area 3
Early warning system Levee system Landfill Dry proofing **Groins*** **Dredge lagoon inlet*** **Corridor protection*** **Improved land use planning***	**Early warning system** **Retention** Landfill Dry proofing **River widening*** **Improved drainage*** **Corridor protection*** **Improved land use planning***	**Early warning system** **Levee system** Landfill Dry proofing **Dredge lagoon inlet*** **Corridor protection*** **Improved land use planning***

4.3. Measures framework simulation

In this section, the results of the framework are given based on the input data (Section 4.1) and the initially chosen measures and areas by Royal HaskoningDHV (2020c) (Section 4.2). The framework was applied on each area from Figure 4.7. To apply the framework to a real sub-area, a component has been added that allows the user to select a sub-area by clicking on the map. Then the input rasters of the entire project area are clipped based on the selected sub-area. The measures from Table 4.3 that can be simulated were selected. The framework results can be found in Table 4.4 and are discussed in the following paragraphs. It can be observed that the calculation time of the framework lies between 14 and 258 seconds. The calculation results for area 1, 2 and 3 are given in Figures 4.8a, 4.8b and 4.8c, respectively. The rest of the output of the framework can be found in Appendix A.

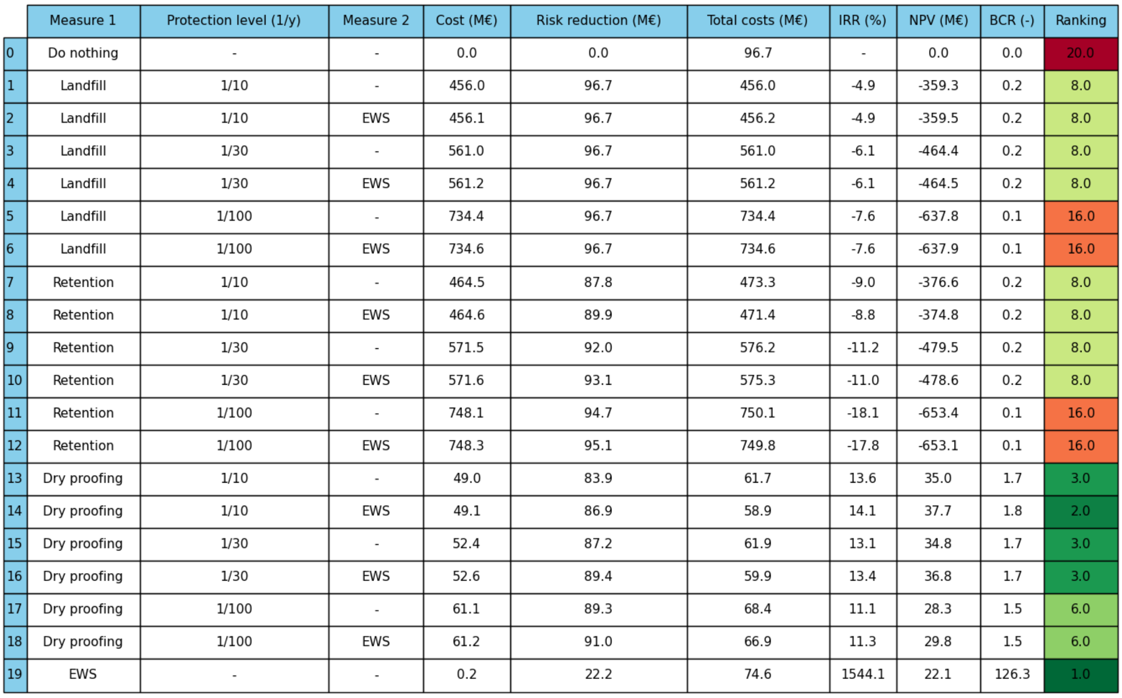
Table 4.4: Calculation time and initially selected measures per area in Phu Loc with chosen measures in bold, according to the framework

	Area 1	Area 2	Area 3
Measures	**Early warning system** **Levee system** Landfill **Dry proofing**	**Early warning system** Retention Landfill **Dry proofing**	**Early warning system** **Levee system** Landfill **Dry proofing**
Calculation time (s)	258	19	14



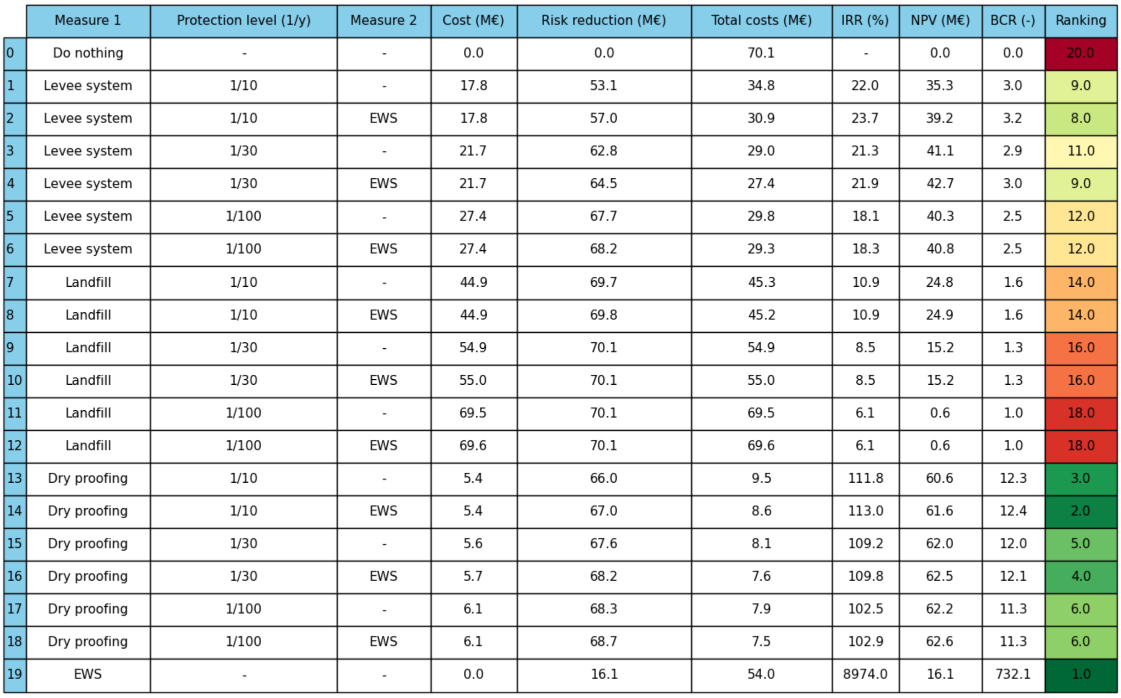
	Measure 1	Protection level (1/y)	Measure 2	Cost (M€)	Risk reduction (M€)	Total costs (M€)	IRR (%)	NPV (M€)	BCR (-)	Ranking
0	Do nothing	-	-	0.0	0.0	204.8	-	0.0	0.0	20.0
1	Levee system	1/10	-	45.2	138.7	111.4	22.6	93.5	3.1	3.0
2	Levee system	1/10	EWS	45.5	153.9	96.4	25.1	108.4	3.4	2.0
3	Levee system	1/30	-	56.6	170.8	90.7	22.3	114.2	3.0	5.0
4	Levee system	1/30	EWS	56.9	178.6	83.1	23.2	121.7	3.1	3.0
5	Levee system	1/100	-	74.2	192.6	86.4	19.1	118.4	2.6	6.0
6	Levee system	1/100	EWS	74.5	195.4	83.9	19.3	120.9	2.6	6.0
7	Landfill	1/10	-	791.3	204.4	791.7	-3.8	-586.9	0.3	14.0
8	Landfill	1/10	EWS	791.5	204.5	791.9	-3.8	-587.0	0.3	14.0
9	Landfill	1/30	-	981.3	204.8	981.4	-5.0	-776.6	0.2	16.0
10	Landfill	1/30	EWS	981.6	204.8	981.7	-5.0	-776.8	0.2	16.0
11	Landfill	1/100	-	1266.4	204.8	1266.4	-6.5	-1061.5	0.2	16.0
12	Landfill	1/100	EWS	1266.6	204.8	1266.6	-6.5	-1061.8	0.2	16.0
13	Dry proofing	1/10	-	92.6	175.3	122.1	15.3	82.7	1.9	9.0
14	Dry proofing	1/10	EWS	92.9	182.1	115.6	16.0	89.2	2.0	8.0
15	Dry proofing	1/30	-	101.3	183.5	122.6	14.5	82.2	1.8	11.0
16	Dry proofing	1/30	EWS	101.6	188.4	118.0	15.0	86.8	1.9	9.0
17	Dry proofing	1/100	-	112.8	188.9	128.8	13.2	76.1	1.7	12.0
18	Dry proofing	1/100	EWS	113.1	192.6	125.4	13.5	79.5	1.7	12.0
19	EWS	-	-	0.3	47.1	158.0	2112.5	46.8	172.6	1.0

(a) Calculation results for area 1



	Measure 1	Protection level (1/y)	Measure 2	Cost (M€)	Risk reduction (M€)	Total costs (M€)	IRR (%)	NPV (M€)	BCR (-)	Ranking
0	Do nothing	-	-	0.0	0.0	96.7	-	0.0	0.0	20.0
1	Landfill	1/10	-	456.0	96.7	456.0	-4.9	-359.3	0.2	8.0
2	Landfill	1/10	EWS	456.1	96.7	456.2	-4.9	-359.5	0.2	8.0
3	Landfill	1/30	-	561.0	96.7	561.0	-6.1	-464.4	0.2	8.0
4	Landfill	1/30	EWS	561.2	96.7	561.2	-6.1	-464.5	0.2	8.0
5	Landfill	1/100	-	734.4	96.7	734.4	-7.6	-637.8	0.1	16.0
6	Landfill	1/100	EWS	734.6	96.7	734.6	-7.6	-637.9	0.1	16.0
7	Retention	1/10	-	464.5	87.8	473.3	-9.0	-376.6	0.2	8.0
8	Retention	1/10	EWS	464.6	89.9	471.4	-8.8	-374.8	0.2	8.0
9	Retention	1/30	-	571.5	92.0	576.2	-11.2	-479.5	0.2	8.0
10	Retention	1/30	EWS	571.6	93.1	575.3	-11.0	-478.6	0.2	8.0
11	Retention	1/100	-	748.1	94.7	750.1	-18.1	-653.4	0.1	16.0
12	Retention	1/100	EWS	748.3	95.1	749.8	-17.8	-653.1	0.1	16.0
13	Dry proofing	1/10	-	49.0	83.9	61.7	13.6	35.0	1.7	3.0
14	Dry proofing	1/10	EWS	49.1	86.9	58.9	14.1	37.7	1.8	2.0
15	Dry proofing	1/30	-	52.4	87.2	61.9	13.1	34.8	1.7	3.0
16	Dry proofing	1/30	EWS	52.6	89.4	59.9	13.4	36.8	1.7	3.0
17	Dry proofing	1/100	-	61.1	89.3	68.4	11.1	28.3	1.5	6.0
18	Dry proofing	1/100	EWS	61.2	91.0	66.9	11.3	29.8	1.5	6.0
19	EWS	-	-	0.2	22.2	74.6	1544.1	22.1	126.3	1.0

(b) Calculation results for area 2



	Measure 1	Protection level (1/y)	Measure 2	Cost (M€)	Risk reduction (M€)	Total costs (M€)	IRR (%)	NPV (M€)	BCR (-)	Ranking
0	Do nothing	-	-	0.0	0.0	70.1	-	0.0	0.0	20.0
1	Levee system	1/10	-	17.8	53.1	34.8	22.0	35.3	3.0	9.0
2	Levee system	1/10	EWS	17.8	57.0	30.9	23.7	39.2	3.2	8.0
3	Levee system	1/30	-	21.7	62.8	29.0	21.3	41.1	2.9	11.0
4	Levee system	1/30	EWS	21.7	64.5	27.4	21.9	42.7	3.0	9.0
5	Levee system	1/100	-	27.4	67.7	29.8	18.1	40.3	2.5	12.0
6	Levee system	1/100	EWS	27.4	68.2	29.3	18.3	40.8	2.5	12.0
7	Landfill	1/10	-	44.9	69.7	45.3	10.9	24.8	1.6	14.0
8	Landfill	1/10	EWS	44.9	69.8	45.2	10.9	24.9	1.6	14.0
9	Landfill	1/30	-	54.9	70.1	54.9	8.5	15.2	1.3	16.0
10	Landfill	1/30	EWS	55.0	70.1	55.0	8.5	15.2	1.3	16.0
11	Landfill	1/100	-	69.5	70.1	69.5	6.1	0.6	1.0	18.0
12	Landfill	1/100	EWS	69.6	70.1	69.6	6.1	0.6	1.0	18.0
13	Dry proofing	1/10	-	5.4	66.0	9.5	111.8	60.6	12.3	3.0
14	Dry proofing	1/10	EWS	5.4	67.0	8.6	113.0	61.6	12.4	2.0
15	Dry proofing	1/30	-	5.6	67.6	8.1	109.2	62.0	12.0	5.0
16	Dry proofing	1/30	EWS	5.7	68.2	7.6	109.8	62.5	12.1	4.0
17	Dry proofing	1/100	-	6.1	68.3	7.9	102.5	62.2	11.3	6.0
18	Dry proofing	1/100	EWS	6.1	68.7	7.5	102.9	62.6	11.3	6.0
19	EWS	-	-	0.0	16.1	54.0	8974.0	16.1	732.1	1.0

(c) Calculation results for area 3

Figure 4.8: Calculation results per measure strategy for area 1, 2 and 3 in Phu Loc

In area 1, the levee system measure is the most appropriate measure. Levee systems combined with an early warning system as well as dry proofing variants lead to positive results of the key performance indicators as well. Although the single early warning system has the highest benefit-cost ratio, the application of this strategy does not have enough effect on the flood risk. The high BCR is caused by the low cost. Strategies with a landfill measure included are less favourable, because the landfill variants have a negative net present value. After the framework simulation in area 1 it is hence interesting to further investigate the levee system, early warning system and dry proofing.

Like in area 1, the framework results for dry proofing are good in area 2. Combinations of dry proofing and an early warning system are also interesting, as these variants have positive net present values. Variants with a landfill and retention measure are costly, caused by the large water volume present in this area during the flood events. This makes the results unfavourable for these measures. Therefore, the early warning system and dry proofing are recommended in area 2 according to the framework.

Dry proofing and early warning system are again favourable measures in area 3. There are also positive key performance indicator results for the levee system. For this measure, the optimum protection level is 1/10 years when looking at the BCR. The landfill measure is also less favourable in this area due to high costs. Apparently, these areas are too large for such a measure. Thus, the early warning system, levee system and dry proofing need to be further analysed for area 3 according to the framework.

4.4. Comparison of the methods

In area 1, the landfill measure was found to be less favourable by both methods. According to the framework, this is due to the high costs, though the risk reduction effects are good. The results for a levee system are different. In the report, the effect of a levee system on the long term is questioned. Caused by climate change, the water levels will rise for all the return periods in Phu Loc. This means that the future protection level of levee systems will decrease. Such considerations are not included in the framework. In terms of cost, the framework estimates (maximum 74.2 M€) and the report estimate

(70.7 M€) are similar. However, nature-based solutions are expected to be cheaper alternatives in the report. Those measures were not simulated by the framework.

For area 2, the results from the two methods are more different. According to the report, retention is an appropriate measure. The proposed location is at an upstream location along the Rui river, which is in the southwest of area 2. Here, a retention area could be built that can delay this river runoff for extreme events. The framework does not consider the location of this retention area. On the other hand, the results show that the water volume in area 2 is large, causing high measure cost. This aspect is not mentioned in the report. However, the retention could in practice be designed for smaller water volumes than currently considered by the framework.

The results in area 3 are more in line with each other. In both the report and the framework, a levee system comes out as a good measure. The mentioned levee system in the report is located at the inlet of the lagoon to reduce erosion at the Lang Co bridge. Because area 3 is the smallest area, the cost of a levee system is lowest. This is clearly shown by the framework. For finding the cost and benefit of the specific levee location, a new simulation of the framework could be done of this smaller area.

The landfill measure is estimated as too expensive in the report for all areas, like in the framework (apart from some variants in area 3). In addition, both methods recommend the early warning system. Dry proofing is expected to be too expensive in the report, while this measure has positive results in the framework. The investment of dry proofing is estimated to be very high in the report. The maximum cost for dry proofing are estimated by the framework at a third (€180 million, all areas combined) of the estimation in the report (€536 million). This difference is mainly caused by the use of different cost data. For the report, the cost estimate for dry proofing is about four times higher (Royal HaskoningDHV, 2020a) than the used cost estimate in the framework. Using the higher cost estimate would lead to a maximum cost of €720 million according to the framework. For areas 1 and 2 this would mean that dry proofing becomes too expensive (see the cost values in Figures 4.8a, 4.8b and 4.8c). Furthermore, in the analytical cost estimate it is assumed that half of the total area consists of buildings, which is where dry proofing can be applied. However, the framework determines this surface area by adding up all locations where the land use involves a building (urban, rural, industry, critical infrastructure and tourism). This creates the remaining difference in the measure cost of dry proofing.

As mentioned in Section 4.2, the chosen protection level in the report was 1/30 years for all considered measures. This decision was not made on beforehand for the framework. In areas 1 and 3 the optimal protection levels shown by the framework are 1/30 years for the levee system measure. However, in area 2, the found optimal protection level by the framework is 1/10 years for the favourable dry proofing measure. In this way, the framework shows that the optimal level of protection can differ per measure and sub-area, contrary to what has been assumed in the report.

4.5. Conclusion

In general, the framework can screen possible adaptation measures rapidly with results that are comparable to the analytical method of RHDHV. Location-bound factors can be considered in analytical decision making but cannot be considered by the framework. This is a consequence of the broad applicability of the framework. In the case of uncertainty, the framework's results can be checked and the argumentation for the measures screening can be expanded with location-bound reasons. The simulations showed that many measures in Phu Loc could not be simulated by the framework, so that the comparison is not entirely complete. These measures require additional hydraulic simulations and therefore do not fit within the method used by the framework (see Section 1.3). The effects of these more complex measures, often nature-based solutions, were also not worked out in detail in the existing method. Despite the fact that these measures are not in the framework, a hydraulic simulation is therefore not necessary in the phase of screening of measures. These measures must, however, be assessed with analytical reasoning. There are some differences between the framework and the report with regard to the measures that have been screened. These differences can be observed for the dry proofing and retention measures and are discussed in Section 7.1.

5

Case study: Waal Eemhaven

This chapter is about the second case study where the framework is applied, which is in the Netherlands. This low-lying country is well protected against floods. However, some areas are still outside the protected land due to practical reasons. These areas will also face the effects of the relative sea level rise. One of those areas is the Waalhaven and the Eemhaven, in short the Waal Eemhaven. It is a part of the port of Rotterdam. It's area is about 800 ha (Royal HaskoningDHV, 2018a). At the Waal Eemhaven are several piers and industrial areas. There is also a residential area, which is called the Heijplaat. A map of this location is shown in Figure 5.1.

Figure 5.1: Overview map of Waal Eemhaven, the Netherlands

This location is not protected by levees, meaning that it is vulnerable to high water levels in the Nieuwe Maas. Although the Maeslant barrier can limit the storm surge from the North Sea, this barrier can fail during storm events when it is not able to close. In addition, climate change can result in higher sea water levels. This means that this location is mainly threatened by coastal flooding. To decrease the flood risk in the Waal Eemhaven, local adaptation measures are therefore required.

In this chapter, the developed framework is applied on the Waal Eemhaven. The input data is given in Section 5.1, where also the results from the existing Global Flood Risk Tool are mentioned. Section 5.2 is about the results from the analytic report of Royal HaskoningDHV (2018a). In Section 5.3, the framework's results are given for some sub-areas within the Waal Eemhaven. The results of both methods are compared in Section 5.4. Finally, Section 5.5 contains a brief conclusion of this case study.

5.1. Input data

In this section, the input data is given for the Waal Eemhaven. This contains the inundation maps, land use map, damage functions, damage maps and the initial flood risk map. In addition, the measure costs and input variables are given. The input data is used for the simulations of the framework in Section 5.3.

The inundation maps are given in Figure 5.2. These maps are made for 2050 where a climate scenario W+ is chosen. This is a warm climate scenario with substantial temperature increase and changed air currents (Klein Tank & Lenderink, 2009). This scenario is interesting to use because the vulnerability of the Waal Eemhaven will increase in the future, especially for warm climate scenarios. For the creation of these maps the WAQUA model of Rijkswaterstaat was used. Six return periods are considered: 10, 100, 300, 1,000, 3,000 and 10,000 years.

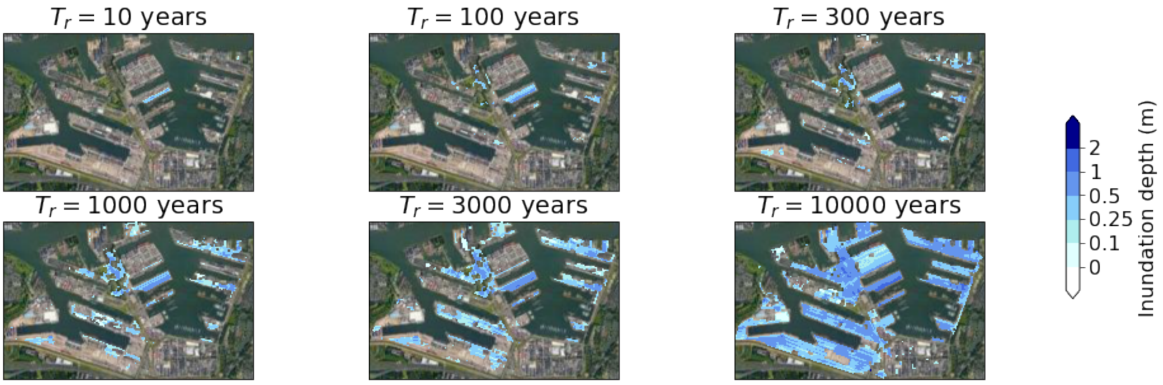


Figure 5.2: Inundation maps for the Waal Eemhaven with return periods of 10, 100, 300, 1,000, 3,000 and 10,000 years

In Figure 5.3 the land uses for the Waal Eemhaven are shown. Note that the area where the land use is defined is not equal to the extent of the inundation maps. For locations where either the inundation depths or the land use is not defined, the flood damages and risk result to zero. For example for the residential area the Heijplaat, for which no land use has been defined (as this area is not part of the risk analysis). The damage functions that correspond with the land uses are shown in Figure 5.4. These functions are used for the damage calculation from in Section 3.1.

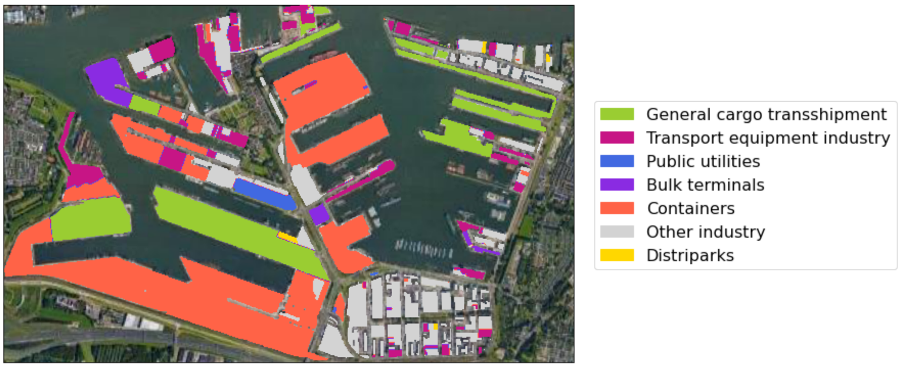


Figure 5.3: Land use map for the Waal Eemhaven

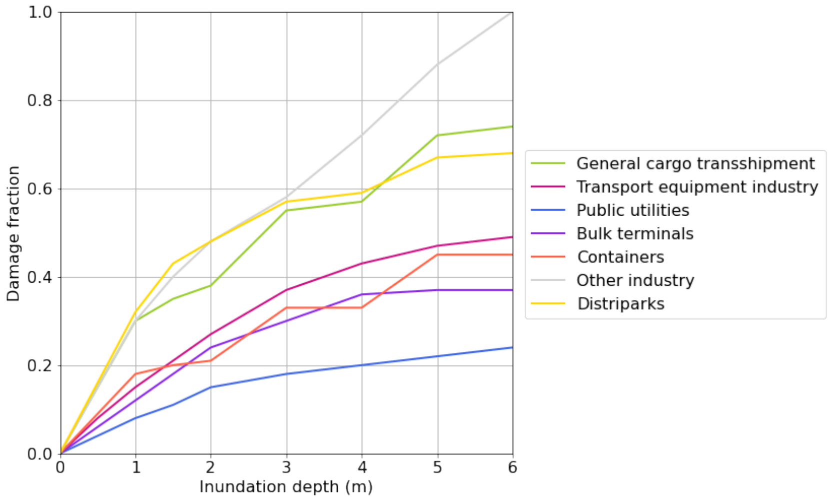


Figure 5.4: Damage functions for the Waal Eemhaven

The current flood damage and risk maps without any applied measures are calculated with the existing Global Flood Risk Tool. The damage maps are shown in Figure 5.5 and the risk map is shown in Figure 5.6. More information about this calculation can be found in Section 3.1.

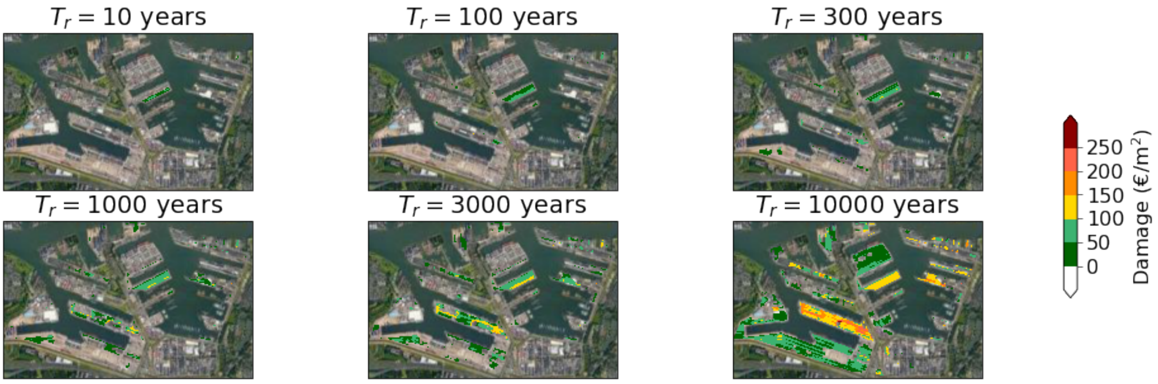


Figure 5.5: Damage maps of the Waal Eemhaven with return periods of 10, 100, 300, 1,000, 3,000 and 10,000 years

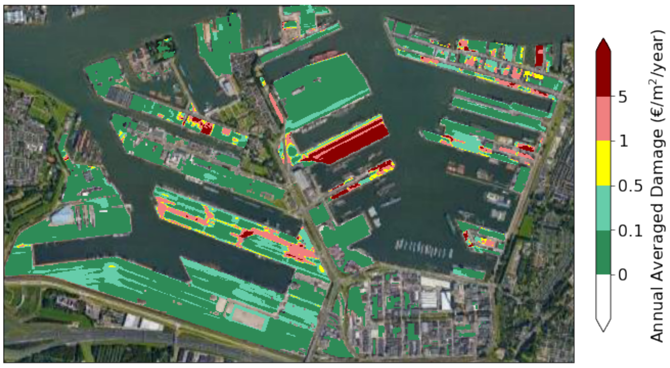


Figure 5.6: Risk map of the Waal Eemhaven in base situation (without any measures applied)

Data for the cost of the adaptation measures can be found in Table 5.1. The table contains information about the investment as well as the operation and maintenance cost per measure for the Waal

Eemhaven, like the tables used for the fictional case and for Phu Loc. Note that the investment cost for a levee system is different per sub-area, discussed in Section 5.2.

Table 5.1: Investment and operation and maintenance cost per adaptation measure in the framework for the Netherlands (*10 applies to Pier 1 and 6, 1.5 applies to Pier 4)

Measure	Investment	Unit	O&M (%)	Source
Spatial relocation	354	€/m^2	0.1	Hillen et al. (2010)
Early warning system	17	€/ha	5.0	Royal HaskoningDHV (2020a)
Levee system	10/1.5*	M€/m/km	0.2	Royal HaskoningDHV (2018b)
Landfill	25	€/m/m^2	0.2	Jonkman et al. (2013)
Water retention	35	€/m^3	1.0	Aerts (2018)
Temporary barrier	5.2	M€/m/km	5.0	Aerts (2018)
Dry proofing	8.7	k€/m/building	2.0	Aerts (2018)
Wet proofing	5.3	k€/m/building	2.0	Aerts (2018)
Elevating buildings	52	k€/m/building	0.2	Aerts (2018)
Delay rainwater runoff	11	€/m^2	0.1	Ecologic Institute and Sendzimir Foundation (2019)
Living shoreline	500	€/m	3.0	Aerts (2018)

Lastly, the input variables for the Waal Eemhaven are given in Table 5.2. These variables can be changed by the user and influence the cost and risk calculations of the applied measures.

Table 5.2: Input variables for the Waal and Eemhaven simulation

Symbol	Description	Value	Unit
$\Delta x, \Delta y$	Grid size	5	m
T	Time horizon	250	years
r	Discount rate	2.9	%
IDF	Indirect damage factor	2	-
A_{building}	Average area per building	2,000	m^2
h_{tb}	Maximum temporary barrier height	1	m
P_f	Failure probability temporary measure	0.1	-
h_{dp}	Maximum dry proofing height	1.5	m
h_{wp}	Maximum wet proofing height	5	m
η_{wp}	Reduction effect wet proofing	0.40	-

Almost all land use types contain buildings. Apart from the containers land use, the dry proofing, wet proofing and elevating measures can be applied everywhere in the Waal Eemhaven. This is different from the Phu Loc case study, where much surface is not built-up.

Like for Phu Loc, the uncertainty analysis is not applied for the Waal Eemhaven due to a lack of investment and operation and maintenance data. The lack of data means that the standard deviations of these parameters cannot be determined. Also for this location, no uncertainty analysis was included in the RHDHV report, which means that the uncertainty results cannot be compared.

5.2. Findings analytical report

This section is about the considered and eventually selected measures from the report of Royal HaskoningDHV (2018a). In the report, an analytical approach is used for the measure selection. The relevant measures according to this report can be found here.

Figure 5.7: Three interesting areas in the Waal Eemhaven (based on Royal HaskoningDHV, 2018a)

In the report of Royal HaskoningDHV (2018a) measures are considered for the Waal Eemhaven within the different layers of the Multi Layered Safety approach (Deltares, 2013). The measures that were selected should be investigated further. Therefore, the report is in line with the function of the framework, which is a screening of measures in an early stage. The report distinguishes several sub-areas within the Waal Eemhaven. Three of these sub-areas are treated here. These areas are Pier 1, Pier 4 and Pier 6 (see Figure 5.7). These sub-areas namely have different results with respect to the selected measures according to the report. The chosen protection level in the report is 1/1,000 years for all measures. This was determined without the specific effects of the measures. The considered measures are given in Table 5.3. These measures are the same for all three sub-areas. In bold are the selected measures after the analysis. In the report, the levee system actually means heightening quays and slopes. This can be interpreted as heightening the edges of the flooded piers. For Pier 1 and 6, those edges are quays, while the edges are slopes for Pier 4. This is why the investment cost is chosen differently per sub-area (Table 5.1). The result for Pier 6 is remarkable, because there is no appropriate measure selected for this area. The measures with star are outside the scope of the framework.

Table 5.3: Initially selected measures per area in Waal Eemhaven with chosen measures in bold, according to Royal HaskoningDHV (2018a) (*measures that cannot be simulated by the framework)

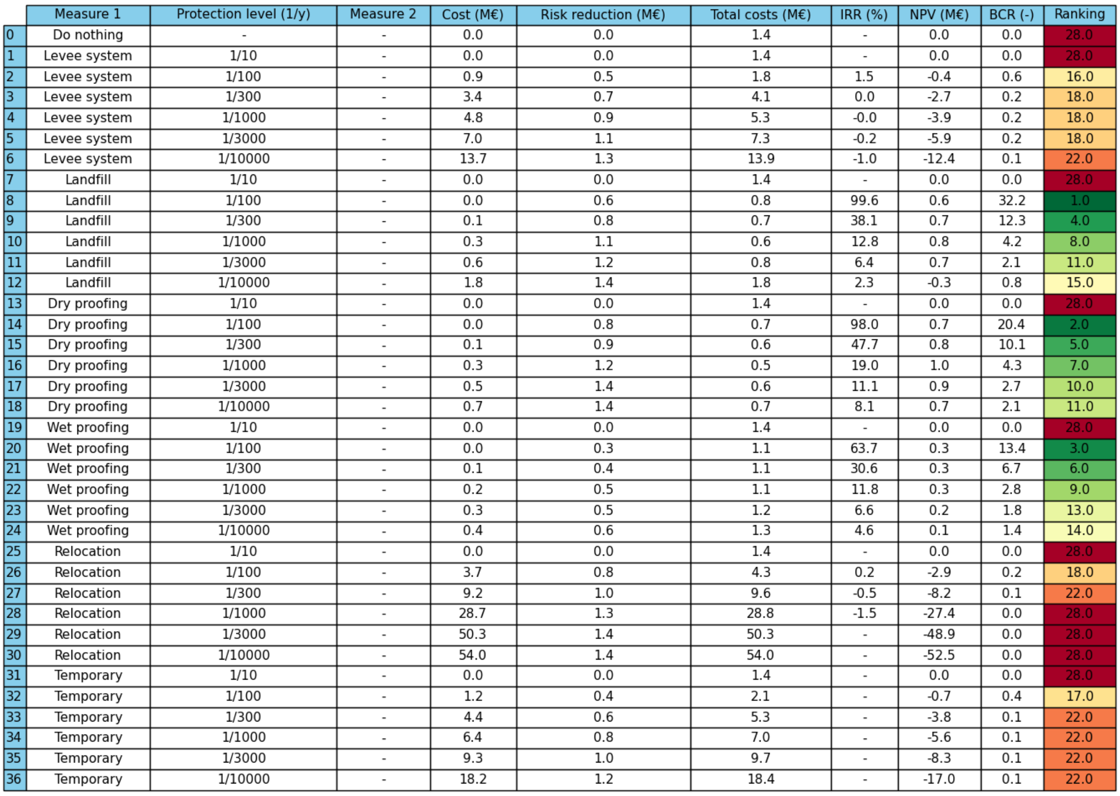
Pier 1	Pier 4	Pier 6
Relocation	Relocation	Relocation
Levee system	**Levee system**	Levee system
Landfill	**Landfill**	Landfill
Temporary barrier	Temporary barrier	Temporary barrier
Dry proofing	Dry proofing	Dry proofing
Wet proofing	Wet proofing	Wet proofing
Compartmentalize subareas*	Compartmentalize subareas*	Compartmentalize subareas*
Storm surge barrier*	Storm surge barrier*	Storm surge barrier*
Function changes*	Function changes*	Function changes*
Emergency measures*	Emergency measures*	Emergency measures*

5.3. Measures framework simulation

With the input data from Section 5.1 and the sub-areas and measures from Section 5.2 (Figure 5.7 and Table 5.3), the framework is applied in the Waal Eemhaven. Just like for Phu Loc, the area selection element added to the framework has been used to clip the rasters based on the sub-areas. The framework results are given in Table 5.4 and are discussed in this section. It can be observed that the calculation time is equal for all three sub-areas, namely 9 seconds. The calculation results for Pier 1, 4 and 6 can be found in Figures 5.8a, 5.8b and 5.8c, respectively. The rest of the output of the framework can be found in Appendix B.

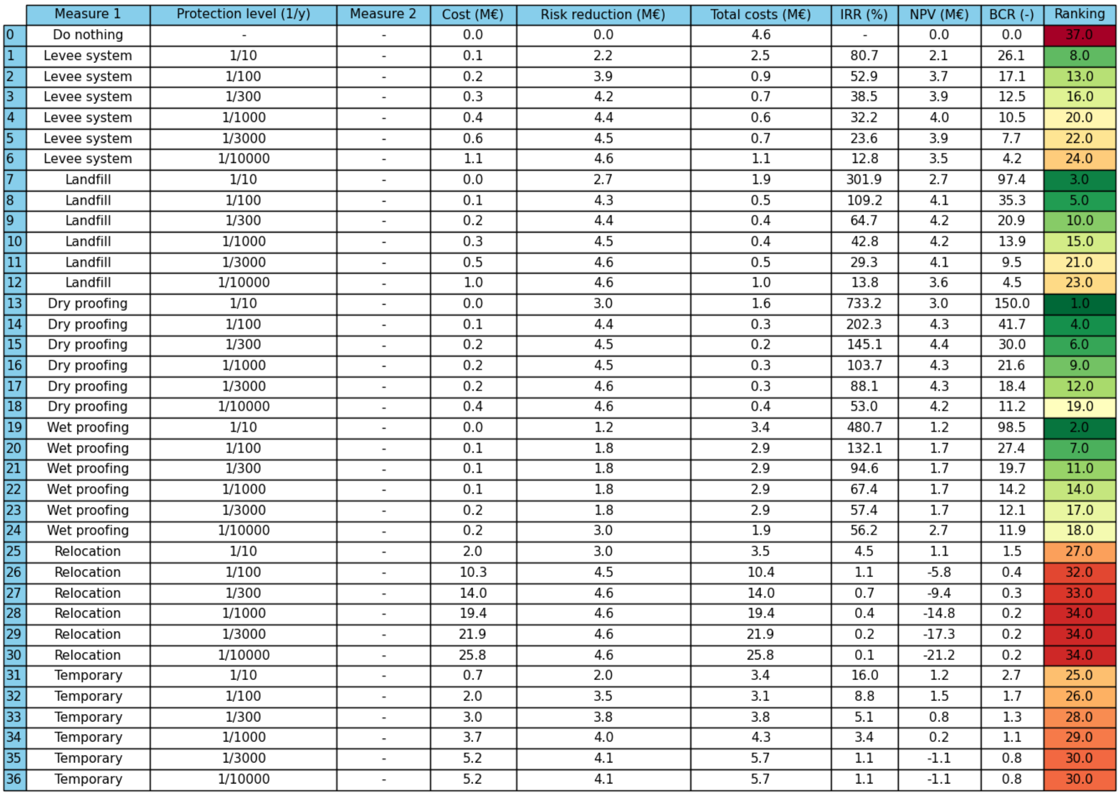
Table 5.4: Calculation time and initially selected measures for Pier 1, 4 and 6 in the Waal Eemhaven with chosen measures in bold, according to the framework

	Pier 1	Pier 4	Pier 6
Measures	Relocation Levee system **Landfill** Temporary barrier **Dry proofing** Wet proofing	Relocation **Levee system** **Landfill** Temporary barrier **Dry proofing** Wet proofing	Relocation Levee system **Landfill** Temporary barrier Dry proofing Wet proofing
Calculation time (s)	9	9	9



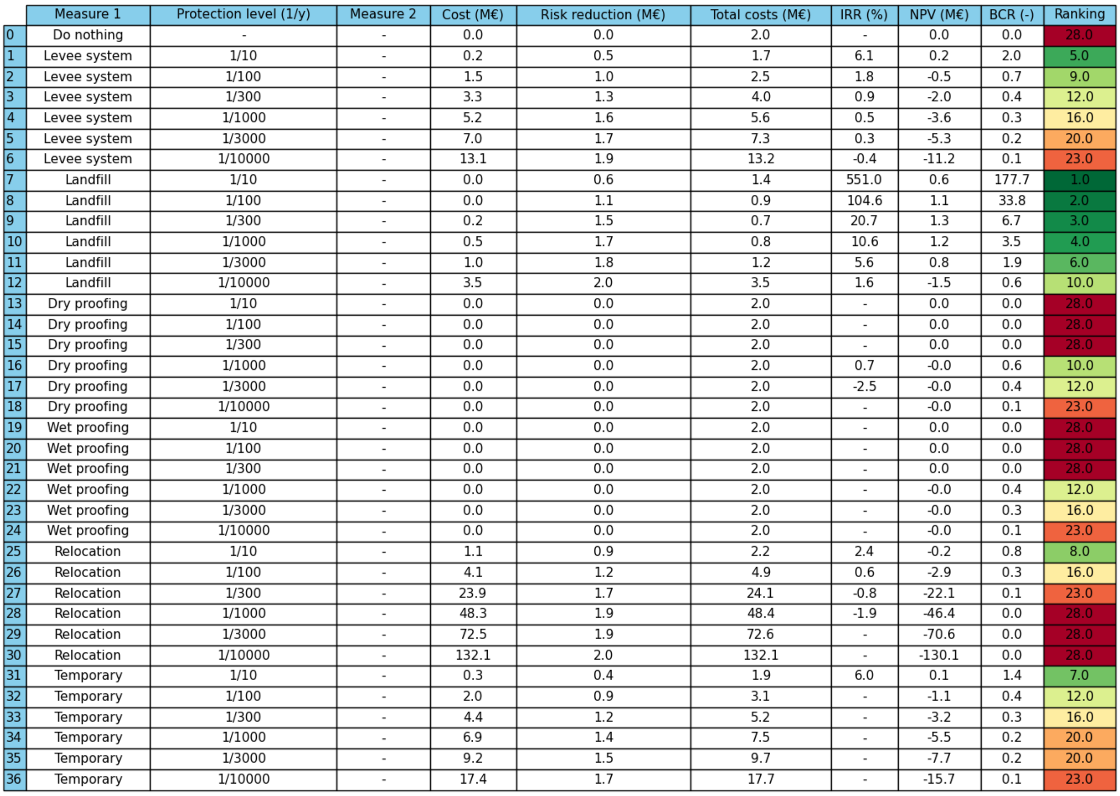
	Measure 1	Protection level (1/y)	Measure 2	Cost (M€)	Risk reduction (M€)	Total costs (M€)	IRR (%)	NPV (M€)	BCR (-)	Ranking
0	Do nothing	-	-	0.0	0.0	1.4	-	0.0	0.0	28.0
1	Levee system	1/10	-	0.0	0.0	1.4	-	0.0	0.0	28.0
2	Levee system	1/100	-	0.9	0.5	1.8	1.5	-0.4	0.6	16.0
3	Levee system	1/300	-	3.4	0.7	4.1	0.0	-2.7	0.2	18.0
4	Levee system	1/1000	-	4.8	0.9	5.3	-0.0	-3.9	0.2	18.0
5	Levee system	1/3000	-	7.0	1.1	7.3	-0.2	-5.9	0.2	18.0
6	Levee system	1/10000	-	13.7	1.3	13.9	-1.0	-12.4	0.1	22.0
7	Landfill	1/10	-	0.0	0.0	1.4	-	0.0	0.0	28.0
8	Landfill	1/100	-	0.0	0.6	0.8	99.6	0.6	32.2	1.0
9	Landfill	1/300	-	0.1	0.8	0.7	38.1	0.7	12.3	4.0
10	Landfill	1/1000	-	0.3	1.1	0.6	12.8	0.8	4.2	8.0
11	Landfill	1/3000	-	0.6	1.2	0.8	6.4	0.7	2.1	11.0
12	Landfill	1/10000	-	1.8	1.4	1.8	2.3	-0.3	0.8	15.0
13	Dry proofing	1/10	-	0.0	0.0	1.4	-	0.0	0.0	28.0
14	Dry proofing	1/100	-	0.0	0.8	0.7	98.0	0.7	20.4	2.0
15	Dry proofing	1/300	-	0.1	0.9	0.6	47.7	0.8	10.1	5.0
16	Dry proofing	1/1000	-	0.3	1.2	0.5	19.0	1.0	4.3	7.0
17	Dry proofing	1/3000	-	0.5	1.4	0.6	11.1	0.9	2.7	10.0
18	Dry proofing	1/10000	-	0.7	1.4	0.7	8.1	0.7	2.1	11.0
19	Wet proofing	1/10	-	0.0	0.0	1.4	-	0.0	0.0	28.0
20	Wet proofing	1/100	-	0.0	0.3	1.1	63.7	0.3	13.4	3.0
21	Wet proofing	1/300	-	0.1	0.4	1.1	30.6	0.3	6.7	6.0
22	Wet proofing	1/1000	-	0.2	0.5	1.1	11.8	0.3	2.8	9.0
23	Wet proofing	1/3000	-	0.3	0.5	1.2	6.6	0.2	1.8	13.0
24	Wet proofing	1/10000	-	0.4	0.6	1.3	4.6	0.1	1.4	14.0
25	Relocation	1/10	-	0.0	0.0	1.4	-	0.0	0.0	28.0
26	Relocation	1/100	-	3.7	0.8	4.3	0.2	-2.9	0.2	18.0
27	Relocation	1/300	-	9.2	1.0	9.6	-0.5	-8.2	0.1	22.0
28	Relocation	1/1000	-	28.7	1.3	28.8	-1.5	-27.4	0.0	28.0
29	Relocation	1/3000	-	50.3	1.4	50.3	-	-48.9	0.0	28.0
30	Relocation	1/10000	-	54.0	1.4	54.0	-	-52.5	0.0	28.0
31	Temporary	1/10	-	0.0	0.0	1.4	-	0.0	0.0	28.0
32	Temporary	1/100	-	1.2	0.4	2.1	-	-0.7	0.4	17.0
33	Temporary	1/300	-	4.4	0.6	5.3	-	-3.8	0.1	22.0
34	Temporary	1/1000	-	6.4	0.8	7.0	-	-5.6	0.1	22.0
35	Temporary	1/3000	-	9.3	1.0	9.7	-	-8.3	0.1	22.0
36	Temporary	1/10000	-	18.2	1.2	18.4	-	-17.0	0.1	22.0

(a) Calculation results for Pier 1



	Measure 1	Protection level (1/y)	Measure 2	Cost (M€)	Risk reduction (M€)	Total costs (M€)	IRR (%)	NPV (M€)	BCR (-)	Ranking
0	Do nothing	-	-	0.0	0.0	4.6	-	0.0	0.0	37.0
1	Levee system	1/10	-	0.1	2.2	2.5	80.7	2.1	26.1	8.0
2	Levee system	1/100	-	0.2	3.9	0.9	52.9	3.7	17.1	13.0
3	Levee system	1/300	-	0.3	4.2	0.7	38.5	3.9	12.5	16.0
4	Levee system	1/1000	-	0.4	4.4	0.6	32.2	4.0	10.5	20.0
5	Levee system	1/3000	-	0.6	4.5	0.7	23.6	3.9	7.7	22.0
6	Levee system	1/10000	-	1.1	4.6	1.1	12.8	3.5	4.2	24.0
7	Landfill	1/10	-	0.0	2.7	1.9	301.9	2.7	97.4	3.0
8	Landfill	1/100	-	0.1	4.3	0.5	109.2	4.1	35.3	5.0
9	Landfill	1/300	-	0.2	4.4	0.4	64.7	4.2	20.9	10.0
10	Landfill	1/1000	-	0.3	4.5	0.4	42.8	4.2	13.9	15.0
11	Landfill	1/3000	-	0.5	4.6	0.5	29.3	4.1	9.5	21.0
12	Landfill	1/10000	-	1.0	4.6	1.0	13.8	3.6	4.5	23.0
13	Dry proofing	1/10	-	0.0	3.0	1.6	733.2	3.0	150.0	1.0
14	Dry proofing	1/100	-	0.1	4.4	0.3	202.3	4.3	41.7	4.0
15	Dry proofing	1/300	-	0.2	4.5	0.2	145.1	4.4	30.0	6.0
16	Dry proofing	1/1000	-	0.2	4.5	0.3	103.7	4.3	21.6	9.0
17	Dry proofing	1/3000	-	0.2	4.6	0.3	88.1	4.3	18.4	12.0
18	Dry proofing	1/10000	-	0.4	4.6	0.4	53.0	4.2	11.2	19.0
19	Wet proofing	1/10	-	0.0	1.2	3.4	480.7	1.2	98.5	2.0
20	Wet proofing	1/100	-	0.1	1.8	2.9	132.1	1.7	27.4	7.0
21	Wet proofing	1/300	-	0.1	1.8	2.9	94.6	1.7	19.7	11.0
22	Wet proofing	1/1000	-	0.1	1.8	2.9	67.4	1.7	14.2	14.0
23	Wet proofing	1/3000	-	0.2	1.8	2.9	57.4	1.7	12.1	17.0
24	Wet proofing	1/10000	-	0.2	3.0	1.9	56.2	2.7	11.9	18.0
25	Relocation	1/10	-	2.0	3.0	3.5	4.5	1.1	1.5	27.0
26	Relocation	1/100	-	10.3	4.5	10.4	1.1	-5.8	0.4	32.0
27	Relocation	1/300	-	14.0	4.6	14.0	0.7	-9.4	0.3	33.0
28	Relocation	1/1000	-	19.4	4.6	19.4	0.4	-14.8	0.2	34.0
29	Relocation	1/3000	-	21.9	4.6	21.9	0.2	-17.3	0.2	34.0
30	Relocation	1/10000	-	25.8	4.6	25.8	0.1	-21.2	0.2	34.0
31	Temporary	1/10	-	0.7	2.0	3.4	16.0	1.2	2.7	25.0
32	Temporary	1/100	-	2.0	3.5	3.1	8.8	1.5	1.7	26.0
33	Temporary	1/300	-	3.0	3.8	3.8	5.1	0.8	1.3	28.0
34	Temporary	1/1000	-	3.7	4.0	4.3	3.4	0.2	1.1	29.0
35	Temporary	1/3000	-	5.2	4.1	5.7	1.1	-1.1	0.8	30.0
36	Temporary	1/10000	-	5.2	4.1	5.7	1.1	-1.1	0.8	30.0

(b) Calculation results for Pier 4



	Measure 1	Protection level (1/y)	Measure 2	Cost (M€)	Risk reduction (M€)	Total costs (M€)	IRR (%)	NPV (M€)	BCR (-)	Ranking
0	Do nothing	-	-	0.0	0.0	2.0	-	0.0	0.0	28.0
1	Levee system	1/10	-	0.2	0.5	1.7	6.1	0.2	2.0	5.0
2	Levee system	1/100	-	1.5	1.0	2.5	1.8	-0.5	0.7	9.0
3	Levee system	1/300	-	3.3	1.3	4.0	0.9	-2.0	0.4	12.0
4	Levee system	1/1000	-	5.2	1.6	5.6	0.5	-3.6	0.3	16.0
5	Levee system	1/3000	-	7.0	1.7	7.3	0.3	-5.3	0.2	20.0
6	Levee system	1/10000	-	13.1	1.9	13.2	-0.4	-11.2	0.1	23.0
7	Landfill	1/10	-	0.0	0.6	1.4	551.0	0.6	177.7	1.0
8	Landfill	1/100	-	0.0	1.1	0.9	104.6	1.1	33.8	2.0
9	Landfill	1/300	-	0.2	1.5	0.7	20.7	1.3	6.7	3.0
10	Landfill	1/1000	-	0.5	1.7	0.8	10.6	1.2	3.5	4.0
11	Landfill	1/3000	-	1.0	1.8	1.2	5.6	0.8	1.9	6.0
12	Landfill	1/10000	-	3.5	2.0	3.5	1.6	-1.5	0.6	10.0
13	Dry proofing	1/10	-	0.0	0.0	2.0	-	0.0	0.0	28.0
14	Dry proofing	1/100	-	0.0	0.0	2.0	-	0.0	0.0	28.0
15	Dry proofing	1/300	-	0.0	0.0	2.0	-	0.0	0.0	28.0
16	Dry proofing	1/1000	-	0.0	0.0	2.0	0.7	-0.0	0.6	10.0
17	Dry proofing	1/3000	-	0.0	0.0	2.0	-2.5	-0.0	0.4	12.0
18	Dry proofing	1/10000	-	0.0	0.0	2.0	-	-0.0	0.1	23.0
19	Wet proofing	1/10	-	0.0	0.0	2.0	-	0.0	0.0	28.0
20	Wet proofing	1/100	-	0.0	0.0	2.0	-	0.0	0.0	28.0
21	Wet proofing	1/300	-	0.0	0.0	2.0	-	0.0	0.0	28.0
22	Wet proofing	1/1000	-	0.0	0.0	2.0	-	-0.0	0.4	12.0
23	Wet proofing	1/3000	-	0.0	0.0	2.0	-	-0.0	0.3	16.0
24	Wet proofing	1/10000	-	0.0	0.0	2.0	-	-0.0	0.1	23.0
25	Relocation	1/10	-	1.1	0.9	2.2	2.4	-0.2	0.8	8.0
26	Relocation	1/100	-	4.1	1.2	4.9	0.6	-2.9	0.3	16.0
27	Relocation	1/300	-	23.9	1.7	24.1	-0.8	-22.1	0.1	23.0
28	Relocation	1/1000	-	48.3	1.9	48.4	-1.9	-46.4	0.0	28.0
29	Relocation	1/3000	-	72.5	1.9	72.6	-	-70.6	0.0	28.0
30	Relocation	1/10000	-	132.1	2.0	132.1	-	-130.1	0.0	28.0
31	Temporary	1/10	-	0.3	0.4	1.9	6.0	0.1	1.4	7.0
32	Temporary	1/100	-	2.0	0.9	3.1	-	-1.1	0.4	12.0
33	Temporary	1/300	-	4.4	1.2	5.2	-	-3.2	0.3	16.0
34	Temporary	1/1000	-	6.9	1.4	7.5	-	-5.5	0.2	20.0
35	Temporary	1/3000	-	9.2	1.5	9.7	-	-7.7	0.2	20.0
36	Temporary	1/10000	-	17.4	1.7	17.7	-	-15.7	0.1	23.0

(c) Calculation results for Pier 6

Figure 5.8: Calculation results per measure strategy for Pier 1, 4 and 6 in the Waal Eemhaven

The first sub-area is Pier 1. From the framework's results here it can be observed that the levee system, relocation and temporary barrier measures are not appropriate. For each of these variants the net present value is negative and the benefit-cost ratio is lower than 1. The wet proofing measure results in only small positive net present values. The cost is too high for the levee system, relocation and temporary barrier, while the benefit is too low for the wet proofing. The most cost-effective variant is a landfill with a protection level of 1/100 years. However, dry proofing with a protection level of 1/1,000 years results in the highest net present value and the lowest total costs. For a next phase the landfill and dry proofing could be investigated further.

For Pier 4 there are large differences in the results per measure. The relocation measure (apart from one variant) does not have good results. The relocation measure is a too expensive option but is effective in the risk reduction. The temporary barrier variants with protection levels of 1/3,000 and 1/10,000 have the same results. The reason for this is the chosen maximum temporary barrier height of 1 m, which is exceeded in the inundation levels with a 10,000-year return period. Some variants of the temporary barrier as well as the wet proofing variants have a positive net present value. However, the levee system, landfill and dry proofing are more appropriate alternatives. Dry proofing is the most cost-effective measure, a protection level of 1/300 years is the best variant for this measure when looking at the net present value and total costs. For this sub-area, the framework therefore suggests to consider the levee system, dry proofing and landfill in the next phase.

For Pier 6 the framework shows again that landfill could be a good measure. The cost for this measure is relatively low and the benefit is a substantial risk reduction. Other measures result in negative or very small positive net present values. The relocation measure has a very poor result, because this requires a higher investment than the initial risk value. The dry and wet proofing measures should not be chosen as well, because Pier 6 almost entirely consists of container areas. As mentioned earlier, dry and wet proofing is not applied on areas with containers. According to the framework, the most appropriate variants are landfills with protection levels of 1/10 or 1/300 years, depending on the performance indicator (benefit-cost ratio or net present value). Thus, the landfill measure is advised to investigate further.

5.4. Comparison of the methods

At Pier 1, the levee system, wet proofing, relocation and temporary barrier measure are not good solutions from both methods. In the report, wet proofing is expected to have an insufficient risk reduction. This also follows from the framework. According to both methods, the high investment cost is the reason for the poor result of the levee system and relocation measures. Dry proofing results in the best solution after both analyses. According to the framework, landfill is also a good measure here. The cost is estimated lower and the benefit higher than in the report. The total terrain to be elevated is lower, while the risk reduction is taken substantially higher (maximum 1.8 M€) than assumed in the report (0.1 M€) (Royal HaskoningDHV, 2018b).

For Pier 4, the measures wet proofing, relocation and temporary barrier are again not appropriate according to both methods. The underlying reasons are the same and were already mentioned for Pier 1. From the methods it turns out that the levee system and landfill measures have positive results. The framework shows that the dry proofing measure is also a good solution. In report, there was no building selected where dry proofing could be applied. Therefore, the cost and benefit of this measure here are not assessed by RHDHV.

In the last sub-area, Pier 6, it is shown that the levee system, dry proofing, wet proofing, relocation and temporary barrier were all inappropriate for both methods. For relocation, the same holds as for the other two sub-areas. The framework shows that dry proofing and wet proofing can barely be applied in this sub-area. Due to the high residual risk, the cost-efficiency is poor for these measures. In the report, one building is considered for dry proofing but this result is also not cost-efficient. The framework gives landfill as the only good solution, while there was no solution found in the report. Like for Pier 1 the difference here is because of the higher benefit. The cost estimates for this measure are about the same (Royal HaskoningDHV (2018b) estimates the cost at 0.5 M€ for a protection level of 1/1,000 years).

Regarding the measure dry proofing the methods differ from each other. In the report a few buildings are assumed that were selected manually. For these buildings the perimeter was determined, the cost for dry proofing are therefore expressed per meter length. On the other side, the framework determines the number of buildings based on the total area and the given area per building (part of the input variables). The cost is therefore expressed per building. For Pier 4 this leads to a different result. In addition, there is a difference in the implementation of the landfill measure. In the report, a constant height is assumed of 0.5 m. The framework calculates the landfill height based on the protection level, leading to spatially different heights. With the same cost estimates in both methods (see Table 5.1) the height differences still lead to different results, especially for Pier 6.

Just like in Phu Loc, a general protection level is assumed for all measures in the report. This protection level is 1/1,000 years. The framework shows that – when dry proofing is chosen for Pier 1 – the optimal protection level is 1/1,000 years as well (highest NPV). When landfill is chosen here, the optimal protection level is also 1/1,000 years, like in the report. For Pier 4, the optimal protection level is 1/300 years for both dry proofing and landfill. At Pier 6, the optimal protection level of 1/300 years is found for the landfill measure. Depending on the sub-area, the optimal protection level is the same or lower than assumed in the report. For the differences, it is important that the framework only considers the economic consequences of the measures, while the protection level was determined based on the acceptable failure probability in the report.

5.5. Conclusion

Also for this case location, the overall results of the framework are comparable to the analytical findings. The cost-benefit analysis was more elaborated in the reference report for this location. Therefore, a better view on the cost and benefit differences could be obtained. Because the framework calculates the effects for every protection level, there is no need for determining a general protection level on beforehand. For this case location, most of the measures from the RHDHV report could be screened using the framework. The largest deviations between the methods are in the landfill and dry proofing measures. These deviations are discussed in Section 7.1.

6

Conclusions

This concluding chapter is about the answers on the research questions. In this thesis a framework has been developed with which measures can be screened on the basis of adjustments to inundation maps, land use maps and damage functions. The framework is intended to provide a faster alternative to the current analytical approach of Royal HaskoningDHV (RHDHV). The following paragraphs provide the answers to the sub-questions from Section 1.3, thereafter these answers are used to answer the main research question.

Sub-question 1: ”What are the current methods for comparing flood adaptation measures and what are the strengths of these methods?”
The analyzed methods for comparing adaptation measures are (see also Section 2.1):

- the current RHDHV method (Royal HaskoningDHV, 2018a, 2020b, 2020c, 2020d);
- analytical formulas (Van Ledden, 2016; Lendering, 2018; Royal HaskoningDHV, 2017);
- analytical performance framework (Lendering et al., 2018);
- FLORES (Van Berchum et al., 2020);
- Adaptation Support Tool (Deltares, 2019);
- FloodRisk (DHI, 2020);
- Flood Modeller (Jacobs, 2020);
- Aqueduct Floods (World Resources Institute, 2020a).

These methods showed that the costs and benefits of measures can be expressed in key performance indicators such as TC, NPV, IRR and BCR. It has also been found that the effects of probability and consequence reducing measures differ from each other. The differences are clearly visible in damage graphs, which show the economic damage as a function of the probability. The use of maps, in which the risks are displayed, is another means of making the effectiveness of measures more transparent. In addition, the structure of the method is clearer if the intermediate steps of the cost-benefit analysis can be seen, for example the expected sizes (quantities) per measure. Finally, the freedom of choice of the user regarding the scope of the measures is greater when the location of the measure can be selected manually. The aforementioned strengths of the existing methods have been included in the composition of the functional requirements.

Sub-question 2: ”What are the functional requirements for the framework?”
Based on the input, which consists of inundation maps, return periods, a land use map, damage functions, (cost) variables and an initial risk map, the framework must simulate the measures. The stated strengths of the existing methods in the first sub-question largely form the functional requirements of the framework (Section 2.3). In addition, it turned out that in the current methods little attention is paid to the uncertainty of the outcomes and that clear overviews showing the adjustable variables are lacking. Therefore, an uncertainty analysis, from which an estimate of the confidence interval of the net present value, and a well-organized input file with all adjustable variables are also functional requirements of the framework. Besides that the framework must be able to determine the optimal measures, it is also

desirable to determine the optimal protection level per measure. Based on these functions, the output of the framework should contain the following seven parts: risk maps, damage graphs, total costs graphs, net present value boxplots, a table with quantities per measure, a table with the results and background information. The background information should show the precise location of the measures and input maps. The purpose of this output is to present all results in a well-organized manner.

Sub-question 3: ”How can the framework be applied to a real case location?”
The framework can be applied to a real case location if this location is included in the existing Global Flood Risk Tool. Namely, inundation maps, a land use map and a current risk map are required as part of the input. To demonstrate the application to a real location, simulations were performed as part of this thesis in Phu Loc, Vietnam (Chapter 4) and the Waal Eemhaven, Rotterdam, The Netherlands (Chapter 5). The recommended measures from the analytical method of RHDHV were compared with the recommended measures from the framework. The results of both methods are generally similar. It can therefore be concluded that the framework is a good alternative to the analytical method of RHDHV. The calculation times were between 9 and 258 seconds, making the framework much faster than using the existing method (order of days). However, it is important that the application of the framework is not possible for every measure, because no hydraulic simulations are performed. This makes the framework most effective in combination with the existing method of RHDHV, in which the more complex measures are considered. It also turned out that performing the uncertainty analysis of the framework requires much data, which is not readily available. Therefore, the uncertainty analysis was not applied in the demonstrations. However, guidelines have been provided for determining the distributions of the variables that are part of the uncertainty analysis.

Main research question: ”How can flood adaptation measures be screened within the risk-based approach to evaluate a list of possible measures without hydraulic modelling each measure?”
This thesis has shown that the developed framework is a way to screen the eleven considered measures without using hydraulic simulations. With the seven forms of output, the results of simulations of the framework are transparent. The framework not only provides the optimal measures but also the optimal protection levels per measure. Adjustments to the variables can be made in a well-organized file and these are immediately implemented in the next simulation. It is a significantly faster alternative to the analytical method of RHDHV, although not every measure can be included in the simulation. Hence, it can be used in combination with the analytical method, which is applied to screen the measures with less direct effects on the inundation depth, like river widening or nourishments.

7

Discussion and recommendations

In this chapter the results are discussed and the limitations of the framework are given. These can be found in Section 7.1. In Section 7.2 the recommendations that follow from the points of improvement are are presented.

7.1. Discussion

This section contains the critical points of the conclusions and developed framework. These points are divided into the interpretation, limitations and consequences. The interpretation is about the meaning of the found results and possible weaknesses of the framework. Elements that are lacking in the framework are discussed in the limitations. In the consequences it is mentioned what the possible effects are of the developed framework and its weaknesses and limitations.

Interpretation

The conclusions showed that the developed framework is a good alternative to the existing method of Royal HaskoningDHV. This was concluded on the basis of the two case locations that have been simulated. These locations are very different from each other. For example, the area size and grid cell size for Phu Loc is considerably larger. The land values and measures costs are also different, because the countries of the locations are in a different development phase. As a result, it is expected that the framework will also be a good alternative to the current method of Royal HaskoningDHV for other locations.

At both Phu Loc and Waal Eemhaven, there are differences between the results of the framework and the current RHDHV method. In Phu Loc, the results of the dry proofing and retention measures are the main differences. For the Waal Eemhaven, this applies to the results of dry proofing and landfill.

The dry proofing measure is estimated differently by the framework compared to the analytical method of Royal HaskoningDHV (2020c) in Phu Loc, especially in terms of cost. It is important to use equal cost data as much as possible, which was not done in the initial simulation. Nevertheless, there was another difference, which had to do with the estimation of buildings and building sizes. For the framework it was chosen to base the buildings on an averaged building area, which can be adjusted by the user. As a result, information is required about the dry proofing cost per building. The reference that was consulted (Aerts, 2018) provided more clarity about the cost per building, which is why this unit is chosen.

In Phu Loc the buildings were estimated more roughly in the analytical assessment than by the framework, but for the Waal Eemhaven this is the other way around. Detailed information available in the Rotterdam port area (such as Google Street View) makes it possible to select certain suitable buildings in the area for flood proofing measures (including dry proofing, wet proofing and elevating buildings). In this way, the perimeter of the selected buildings can also be properly estimated. This advantage of the Waal Eemhaven has been applied in the analytical method from the report (Royal HaskoningDHV, 2018a), but cannot be taken into account by the framework. The framework can only extract building information from the land use. Because of the chosen general method of the framework, it is also possible to determine the costs and benefits with little information (such as in Phu Loc), so that specific information is not used. However, it can be assessed in advance whether there are suitable buildings in the area for flood proofing, and the land use types that contain buildings can be adjusted.

The retention measure has a general effect in the framework. Namely, the principle is to transport excess water from an area to a retention location, where the water can be stored (Section 3.3). The effect differs from the effect of a water storage location along a river, which reduces the river discharge. In this case, the stored river water does not reach the previously flooded area. This means that there are no sewage systems or runoff canals required, leading to lower cost of a storage location along a river. The currently implemented retention measure has a high cost for larger inundation volumes and is therefore an unfavourable measure in large areas like the sub-areas in Phu Loc. Because of the chosen effect of the retention measure in the framework, water storage in general does not have to be an inappropriate measure if the framework shows poor results.

As described in Section 5.4, it was chosen for the framework to not use a constant land elevation in the landfill measure, as is done in the report of Royal HaskoningDHV (2018a) for the Waal Eemhaven. Instead, the elevation varies depending on the initial inundation depth, with a return period corresponding to the protection level of the landfill (Section 3.3). Adopting a constant elevation provides more clarity about the extent of this measure and may be detailed enough in the measure screening phase. At the same time, the elevation could then only be related to e.g. the maximum inundation depth that occurs in the area. When the maximum depths differ little per return period, it is more difficult to distinguish between the different protection levels of the landfill measure. Moreover, by working with spatially varying elevations, the measure is estimated more effectively because less elevation is required. With the quantity table, the quantities can easily be compared with other methods, e.g. when the reference method uses a constant landfill elevation.

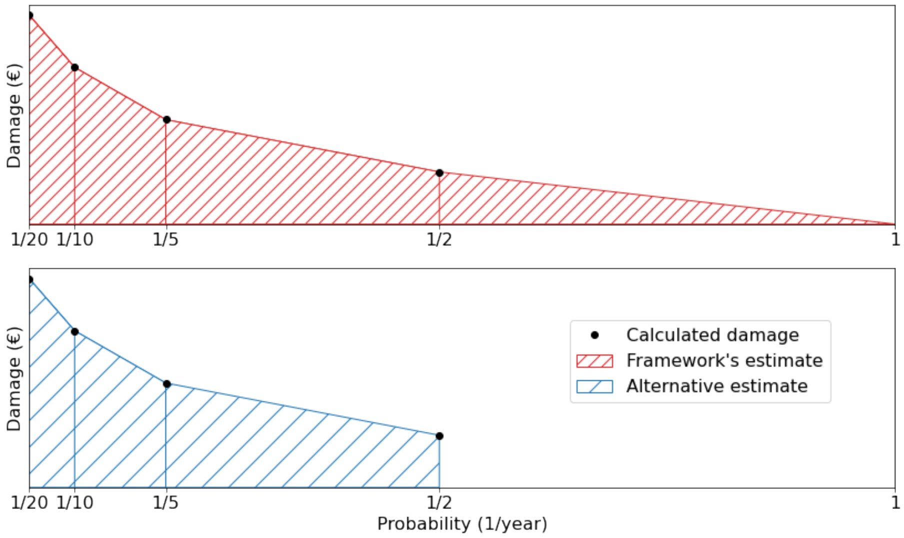


Figure 7.1: Difference in flood risk estimates from the damage curve between the framework (upper graph) and Jonkman et al. (2018) (lower graph)

Not only the comparison with the RHDHV method is a way of looking critically at the framework. Assumptions are also made in the existing method that are not correct in every situation. The main assumption is the way in which the flood risk is calculated. As mentioned in Section 3.1, the assumption is that damage occurs for each return period, also for return periods shorter than the shortest period taken into account in the damage calculations. However, this is not always correct, for example when an area is protected from flood events with shorter return periods. That is why it is often assumed in economic risk calculations to only consider damage for return periods equal or greater than the shortest considered return period (see for example Jonkman et al., 2018). This difference is shown in Figure 7.1. However, the alternative flood risk calculation can lead to an underestimation.

One aspect of the framework is the ability for the user to choose or adjust the input. This means that much input is required before the simulation can take place. Establishing the input takes significantly longer than the simulation itself. So, although this input must also be determined for other methods, the total time to use the framework is longer than the stated 258 seconds. In addition, the freedom of input choice for the user means that the framework becomes sensitive for errors. When an incorrect cost estimate is provided, the cost and key performance indicators are also incorrect. This can of course be directly linked to a wrong input value. However, if the provided inundation maps or land use map are incorrect, the error cannot be detected immediately from the results. Therefore, it is important as a user to look critically at the initial risk map and check whether it is realistic.

To assess the simulation results of the framework - without making a comparison with an existing report - one can look at the order size. For the simulated case locations it can be seen that both the costs and the risk reduction are in the order of million euros, which seems realistic. However, there is one measure for which this does not apply, namely the early warning system. The costs of this measure are estimated to be less than 1 million euros, which means that the benefit-cost ratio has an unreal and high value for this measure. A reason for this is the low cost estimate that has been assumed, but the simulated areas were also relatively small for the application of such a measure. Early warning systems are used in large cities, provinces or small countries such as the FEWS in the Netherlands (Rijkswaterstaat, 2011).

Limitations

Despite the speed and results of the simulations, the framework has some limitations. For example, eleven measures have been chosen that are included in the framework. In this, no measures have been chosen that require additional hydraulic simulations. Including these measures would mean that a model would have to be used for the considered area to determine how the flood depths change due to these measures. Economically oriented measures such as flood insurance have also not been included. For example, the costs for insurance not only consist of the expected direct damage, but also include determining this risk, marketing, personnel and profit margin (Karapiperis et al., 2017). It is therefore difficult to estimate the cost of such measures, especially in the screening phase of the decision making process.

In addition, the framework is limited to only the economic flood risk. This means that other risk categories are not considered, for both the current situation and the measure effects. Environmental effects of measures are becoming increasingly transparent and policy is conducted to include these effects at an early stage in the assessment of solutions (European Environment Agency, 2016). In addition, maximum values for socio-economic risk apply in developed countries. For example, the maximum local individual risk (LIR) in the Netherlands is 1/100,000 per year (STOWA & Rijkswaterstaat, 2017). The economically most attractive measures are therefore not always the right solutions, it is important to be aware of this when applying the results of the framework.

Although the input for the uncertainty analysis is chosen by the user, it would be useful to apply the uncertainty analysis to the case locations. This makes it possible to see how this element of the framework can be used for new locations. This was not possible due to the lack of data with spreads of cost estimates per measure. After all, the uncertainty analysis is intended to gain insight into the uncertainty of the outcome, this can only be done if information is available about the variables where the result depends on. The uncertainty analysis distinguishes the framework from the investigated existing methods, which do not have this function. For the comparison of results with the current method of RHDHV as done in Chapters 4 and 5, not performing this analysis is therefore less important.

Consequences

Due to the good results, it is useful to use the framework in the initial phase of advising adaptation strategies. The developed framework consists of offline Python code. To make it easier to use, the framework should be added to the online Global Flood Risk Tool, so that the user no longer needs knowledge of Python to use it properly and it becomes more accessible. In addition, the framework forms an alternative to existing tools. However, the current framework will not be immediately distinctive. Because it only contains 11 measures, tools like FloodRisk (DHI, 2020) are more attractive.

Moreover, without data for spreads of the cost estimations, the uncertainty analysis cannot be properly applied, which is one of the key elements of the framework. Another reason to choose a different tool is that the framework only focuses on the economic risk. It is therefore important to continue to develop the framework. The above mentioned aspects lead to the recommendations described in the next section.

7.2. Recommendations

This section presents the recommendations for further research and framework improvements, based on the findings from the previous section. These are ordered by priority (1 is most important, 6 is least important). The recommendations are as follows:

1. **Adding an extensive cost database**
   Before the simulations could be performed, cost estimates were required per measure for the locations of application. Compiling these estimates is time-consuming, as it involves many different types of measures, not all of which have been previously applied at the locations. When an extensive cost database is linked to the framework, the estimates per simulation can quickly be determined using the location/country. In addition, spreads of the cost values can be included in the cost database, so that the uncertainty analysis can be carried out more easily. Such a cost database can in itself also be of value to RHDHV (separate from the framework). The lack of cost data sets was the reason for not performing an uncertainty analysis for the case locations in this thesis.

2. **Analyzing reduction effects**
   Part of the input variables are reduction factors for some measures. This concerns the living shoreline, wet proofing and early warning system measures. Although the reduction factors are adjustable, more knowledge about these reductions can remove uncertainty about the effects of these measures on the risk. More knowledge lowers the model uncertainty, which is difficult to estimate and is therefore not included in the uncertainty analysis.

3. **Implementing moment of intervention**
   The simulations performed are based on a snapshot in time of the case locations. In this way, the simulations could also be performed for other moments in time (e.g. now, in 30 years and in 80 years). At some point in time the risk becomes greater than the acceptable level. On the other hand, there is an economically optimal time to invest (see Veenman, 2019). On the basis of these two aspects, it can be determined for which time scenario measures must be taken. Expanding the framework with this is of added value for the screening of measures.

4. **Taking into account other types of risk**
   The current framework only bases the screening of the measures on the economic flood risk. As described in Section 1.1, there are also other types of flood risk, namely the socio-economic and environmental risk. When the effects of the measures are also simulated for these risk types, the screening is even more complete. Preventing the failure of critical infrastructure or release of pollutants into the environment can be a trigger to take action. In addition, the local individual risk and the social risk must be below the acceptable levels. Measures that perform well economically can have too little effect on the other risk types, so that realization is still not desirable. Therefore, including other types of risk in the framework is another way to improve the screening of measures.

5. **Supporting the framework with a hydraulic model**
   The current framework can simulate the costs and effects of 11 different types of measures. Still, more measures are applied in practice, see for example the measures discussed in Section 2.2. Almost all existing tools are capable of simulating measures with more complex effects on the inundation depth, which are not included in the framework due to the scope of this thesis. These tools contain an underlying hydraulic model. Adding such a model to the framework therefore makes it possible to simulate more measures. Since the framework is intended for screening measures, such a model could work with simple assumptions, which keeps the simulation time low.

6. **Investigating the addition of dynamic modelling**
   DHI's tool FloodRisk (DHI, 2020) showed that dynamic modeling can be used for the flood simulations (see Section 2.1). This way of modeling implies that the inundation depth varies during the flood event, providing a better insight into the course of flood events. It could be investigated how this advanced form of modeling can be implemented in the framework.

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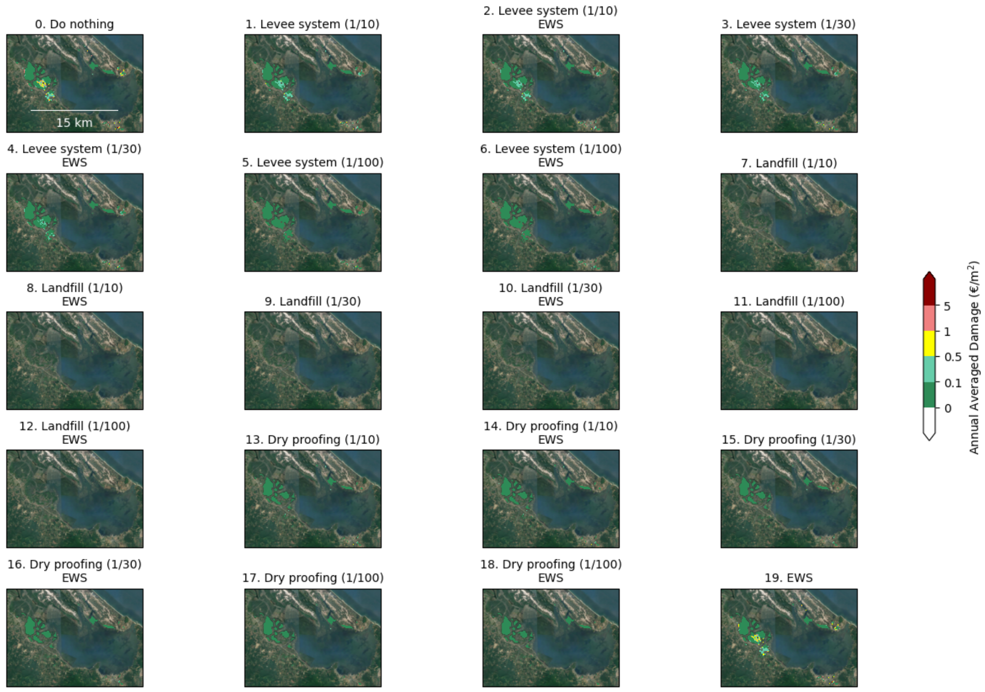
A

Framework output Phu Loc

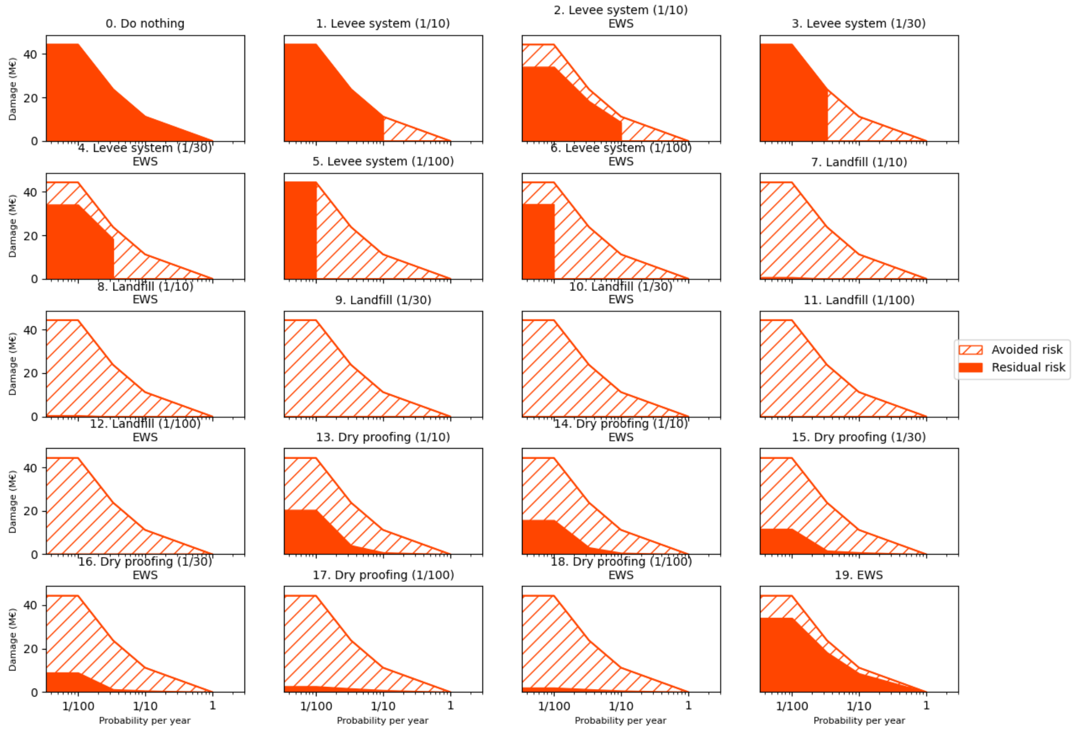
This appendix contains the framework's output from the simulations in the case study area Phu Loc. As mentioned in Chapter 4, three sub-areas were selected within the Phu Loc district. These areas correspond with the chosen areas in the report of Royal HaskoningDHV (2020c). The orientation of these areas can be found in Figure 4.7. The calculation results are given in Section 4.3. The rest of the framework's output for areas 1, 2 and 3 is given in Sections A.1, A.2 and A.3 respectively. Note that the uncertainty analysis is not included, as mentioned in Section 4.1.

A.1. Area 1

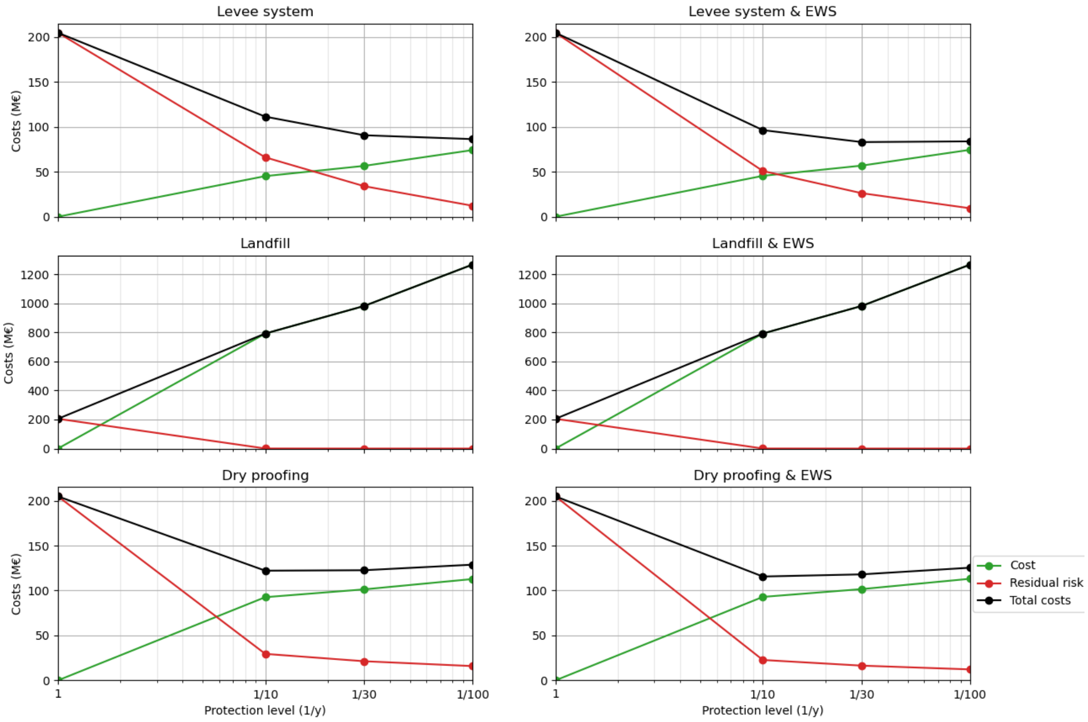
Area 1 is the largest area and contains the Cau Hai lagoon. In this area, the selected measures for the framework simulation were levee system, landfill, dry proofing and early warning system. The risk maps, damage graphs, cost graphs, NPV graph and quantities table can be found in Figures A.1a, A.1b, A.1c, A.1d and A.1e respectively. The background information is shown in Figures A.1f and A.1g. The calculation results are given in Section 4.3.



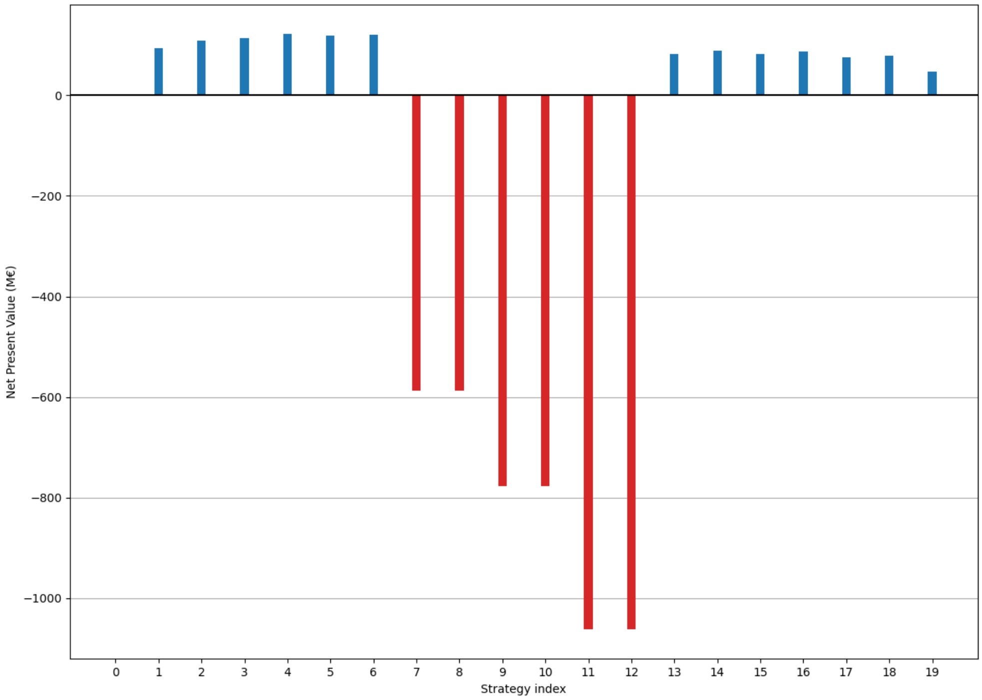
(a) Residual risk maps per measure strategy



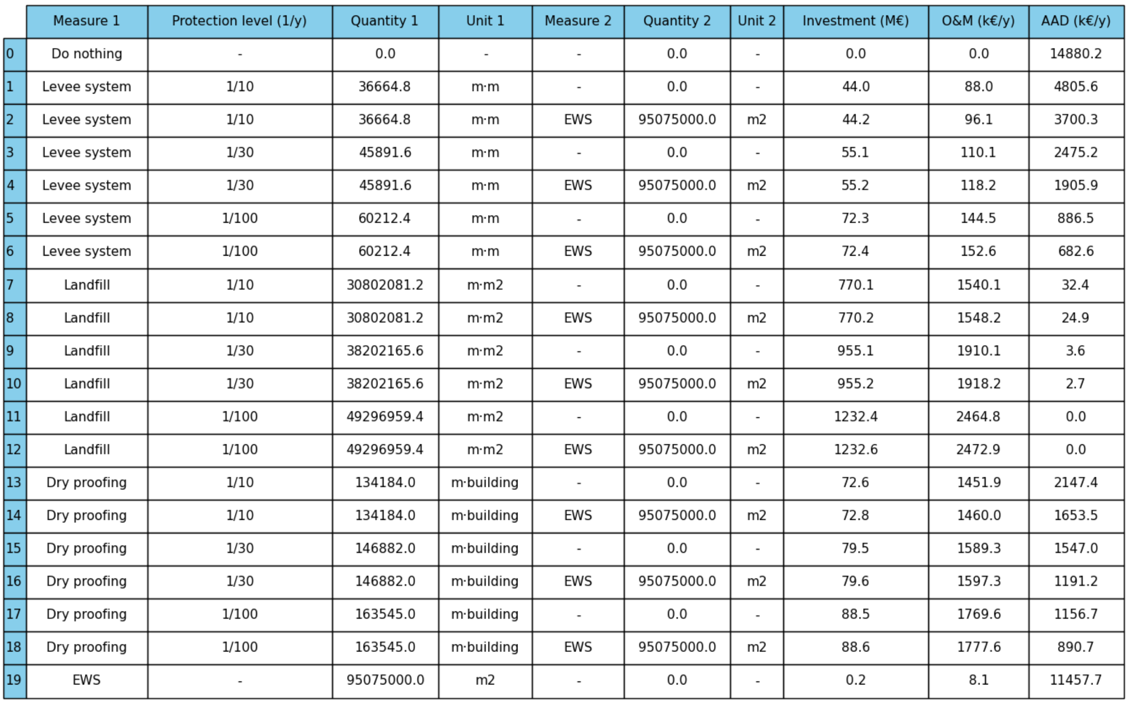
(b) Damage graphs per measure strategy. On the horizontal axis is the probability per year and on the vertical axis is the direct economic damage.



(c) Cost graphs per measure. On the horizontal axis is the design protection level and on the vertical axis is the cost.

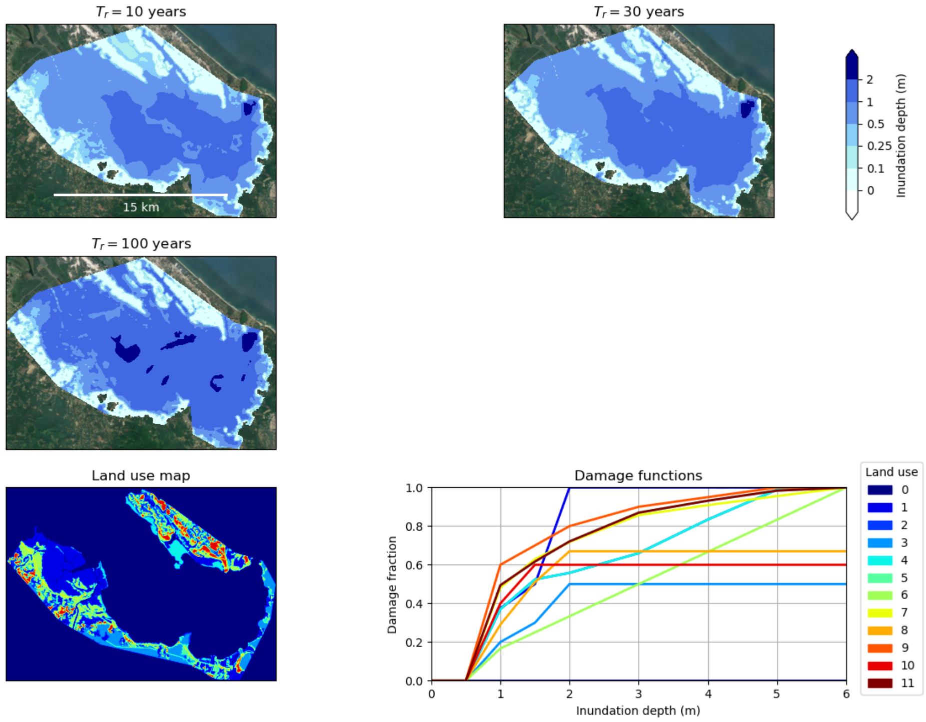


(d) Net present value graph. On the horizontal axis is the strategy index and on the vertical axis is the net present value.

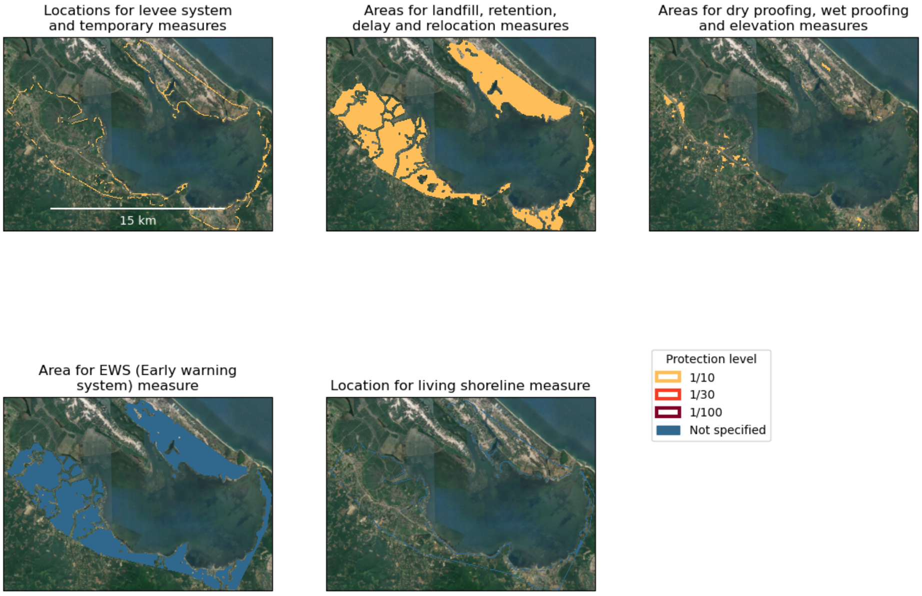


	Measure 1	Protection level (1/y)	Quantity 1	Unit 1	Measure 2	Quantity 2	Unit 2	Investment (M€)	O&M (k€/y)	AAD (k€/y)
0	Do nothing	-	0.0	-	-	0.0	-	0.0	0.0	14880.2
1	Levee system	1/10	36664.8	m·m	-	0.0	-	44.0	88.0	4805.6
2	Levee system	1/10	36664.8	m·m	EWS	95075000.0	m2	44.2	96.1	3700.3
3	Levee system	1/30	45891.6	m·m	-	0.0	-	55.1	110.1	2475.2
4	Levee system	1/30	45891.6	m·m	EWS	95075000.0	m2	55.2	118.2	1905.9
5	Levee system	1/100	60212.4	m·m	-	0.0	-	72.3	144.5	886.5
6	Levee system	1/100	60212.4	m·m	EWS	95075000.0	m2	72.4	152.6	682.6
7	Landfill	1/10	30802081.2	m·m2	-	0.0	-	770.1	1540.1	32.4
8	Landfill	1/10	30802081.2	m·m2	EWS	95075000.0	m2	770.2	1548.2	24.9
9	Landfill	1/30	38202165.6	m·m2	-	0.0	-	955.1	1910.1	3.6
10	Landfill	1/30	38202165.6	m·m2	EWS	95075000.0	m2	955.2	1918.2	2.7
11	Landfill	1/100	49296959.4	m·m2	-	0.0	-	1232.4	2464.8	0.0
12	Landfill	1/100	49296959.4	m·m2	EWS	95075000.0	m2	1232.6	2472.9	0.0
13	Dry proofing	1/10	134184.0	m·building	-	0.0	-	72.6	1451.9	2147.4
14	Dry proofing	1/10	134184.0	m·building	EWS	95075000.0	m2	72.8	1460.0	1653.5
15	Dry proofing	1/30	146882.0	m·building	-	0.0	-	79.5	1589.3	1547.0
16	Dry proofing	1/30	146882.0	m·building	EWS	95075000.0	m2	79.6	1597.3	1191.2
17	Dry proofing	1/100	163545.0	m·building	-	0.0	-	88.5	1769.6	1156.7
18	Dry proofing	1/100	163545.0	m·building	EWS	95075000.0	m2	88.6	1777.6	890.7
19	EWS	-	95075000.0	m2	-	0.0	-	0.2	8.1	11457.7

(e) Quantities and yearly cost/risk per measure strategy



(f) Overview of the input (inundation maps, land use map and damage functions)

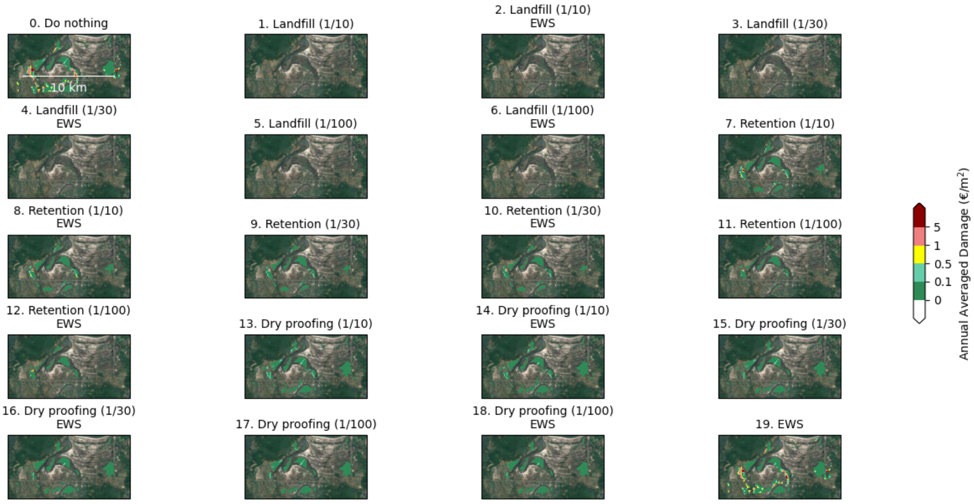


(g) Extents of the measures in the area

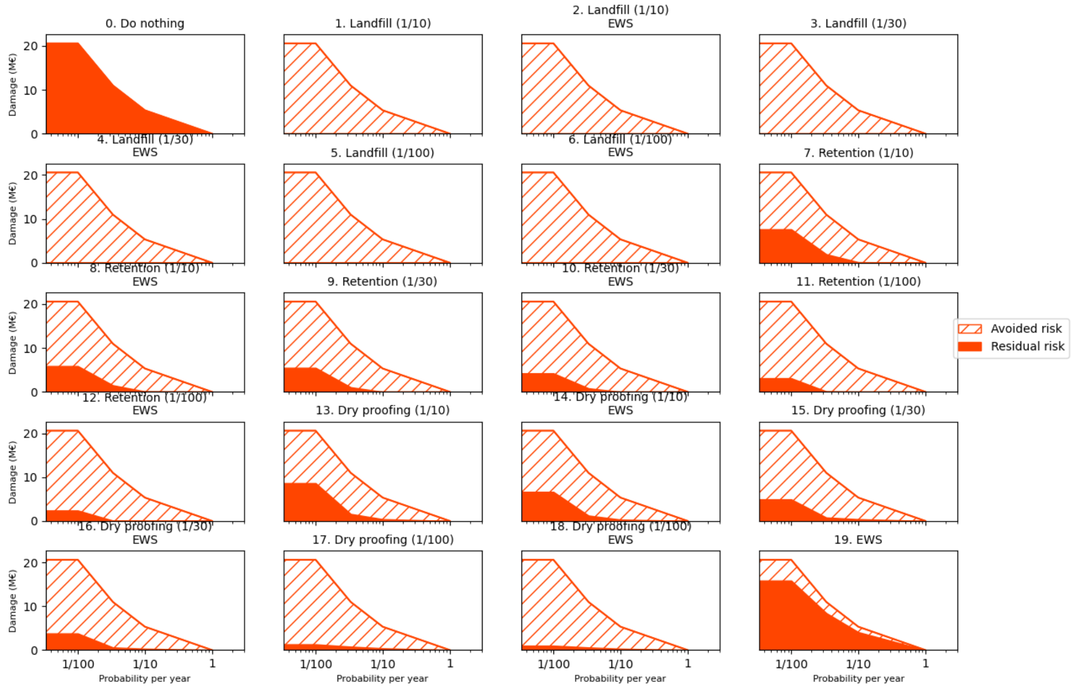
Figure A.1: Remaining part output framework for area 1

A.2. Area 2

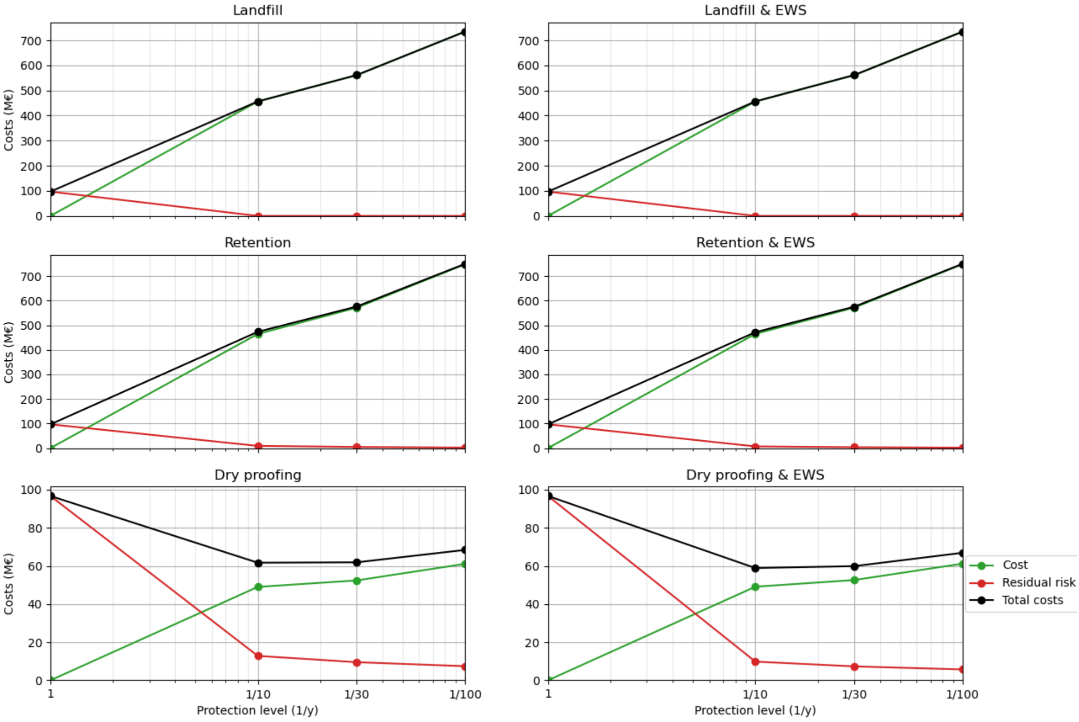
This area is located in a mostly urban area between the two lagoons. The selected measures in this area were landfill, retention, dry proofing and early warning system. The risk maps, damage graphs, cost graphs, NPV graph and quantity table can be found in Figures A.2a, A.2b, A.2c, A.2d and A.2e respectively. The background information is shown in Figures A.2f and A.2g. The calculation results are given in Section 4.3.



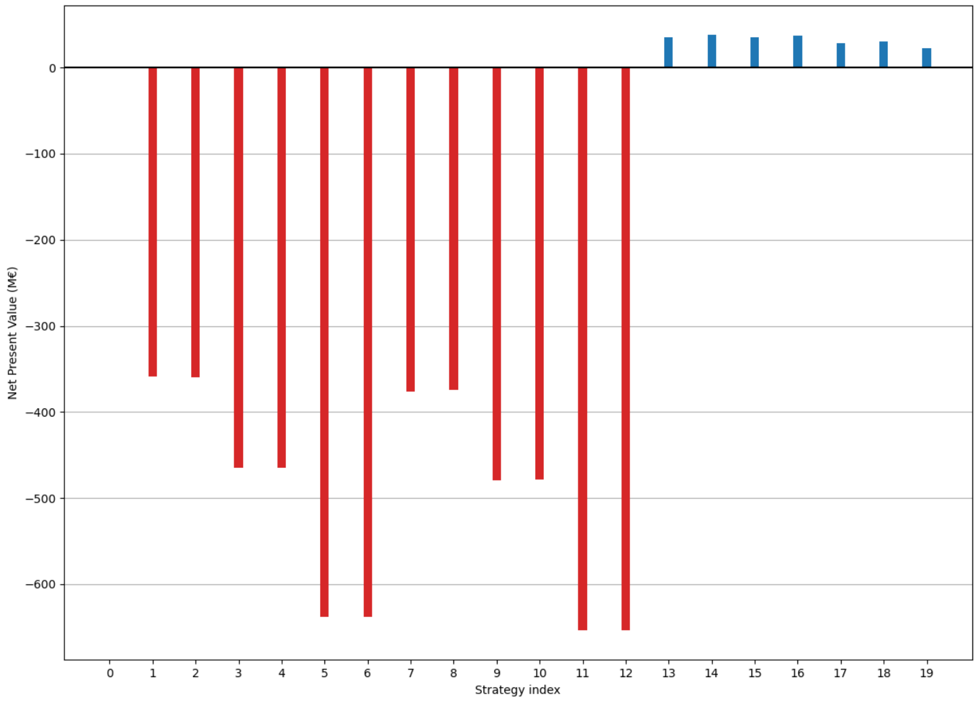
(a) Residual risk maps per measure strategy



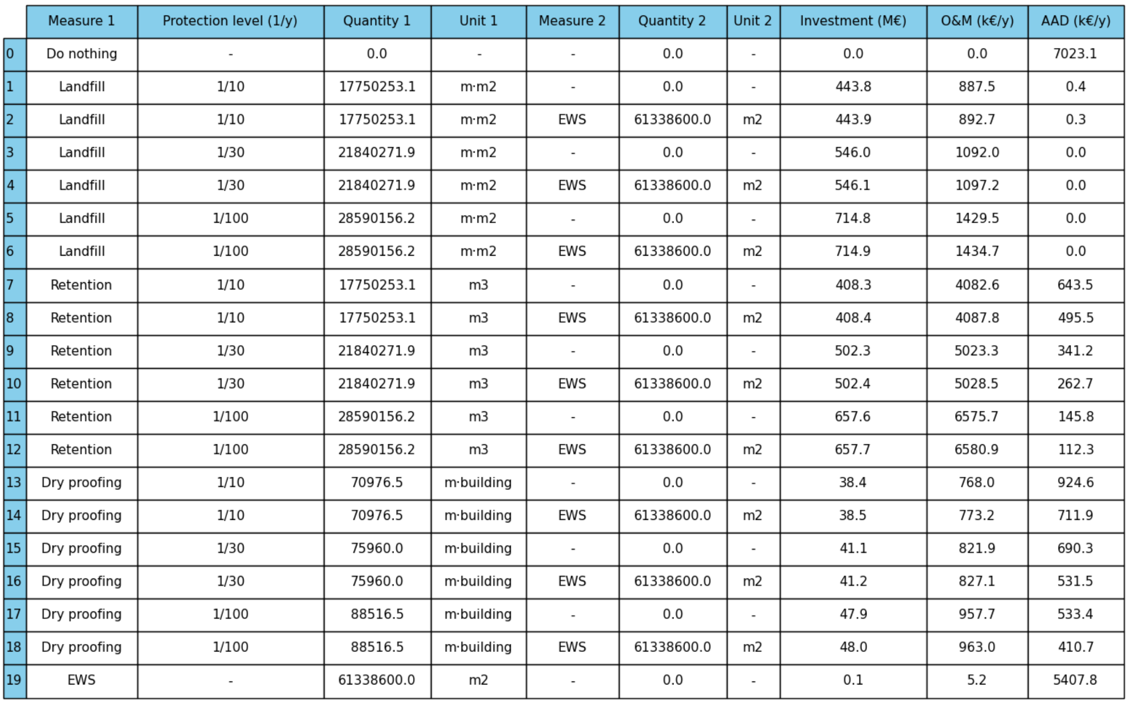
(b) Damage graphs per measure strategy. On the horizontal axis is the probability per year and on the vertical axis is the direct economic damage.



(c) Cost graphs per measure. On the horizontal axis is the design protection level and on the vertical axis is the cost.

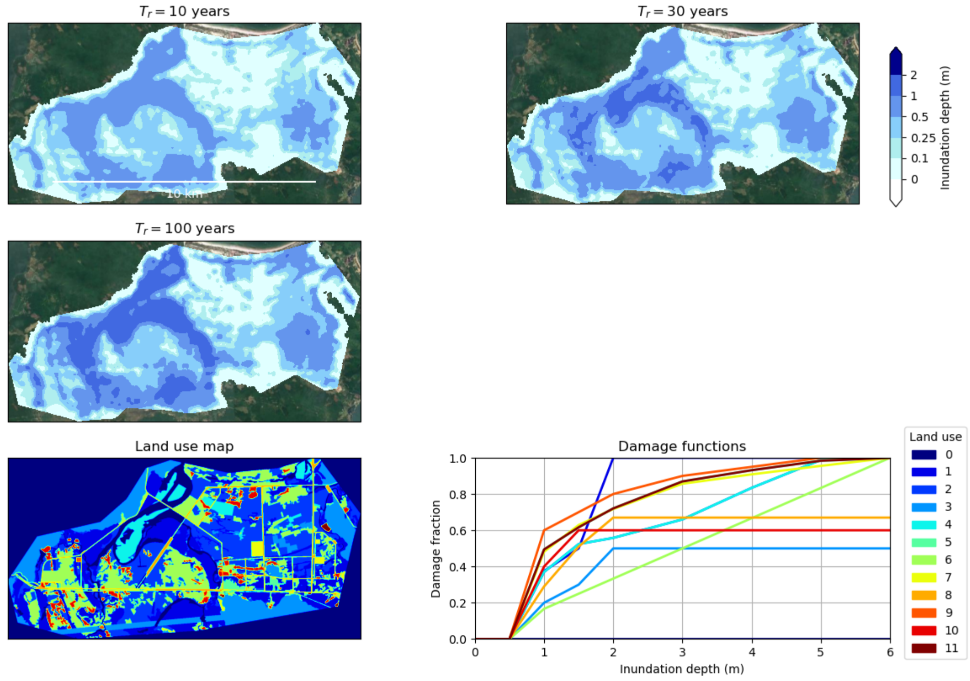


(d) Net present value graph. On the horizontal axis is the strategy index and on the vertical axis is the net present value.

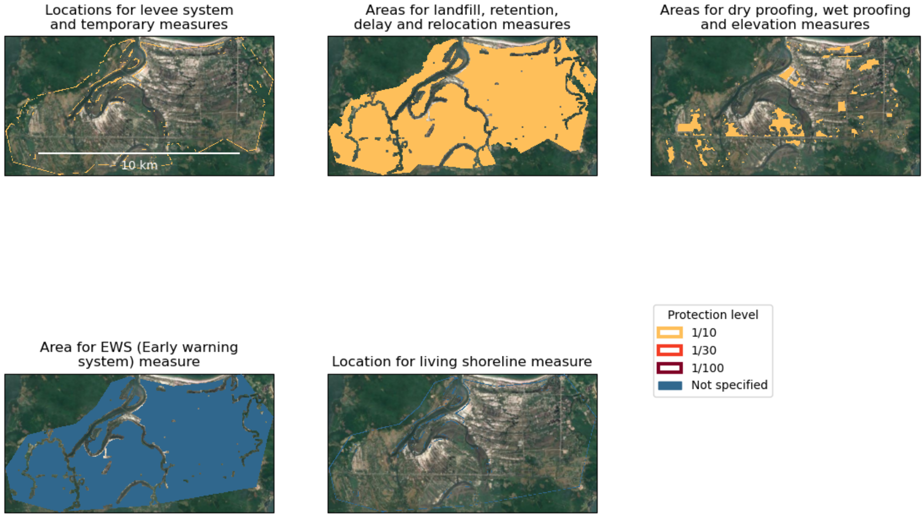


	Measure 1	Protection level (1/y)	Quantity 1	Unit 1	Measure 2	Quantity 2	Unit 2	Investment (M€)	O&M (k€/y)	AAD (k€/y)
0	Do nothing	-	0.0	-	-	0.0	-	0.0	0.0	7023.1
1	Landfill	1/10	17750253.1	m·m2	-	0.0	-	443.8	887.5	0.4
2	Landfill	1/10	17750253.1	m·m2	EWS	61338600.0	m2	443.9	892.7	0.3
3	Landfill	1/30	21840271.9	m·m2	-	0.0	-	546.0	1092.0	0.0
4	Landfill	1/30	21840271.9	m·m2	EWS	61338600.0	m2	546.1	1097.2	0.0
5	Landfill	1/100	28590156.2	m·m2	-	0.0	-	714.8	1429.5	0.0
6	Landfill	1/100	28590156.2	m·m2	EWS	61338600.0	m2	714.9	1434.7	0.0
7	Retention	1/10	17750253.1	m3	-	0.0	-	408.3	4082.6	643.5
8	Retention	1/10	17750253.1	m3	EWS	61338600.0	m2	408.4	4087.8	495.5
9	Retention	1/30	21840271.9	m3	-	0.0	-	502.3	5023.3	341.2
10	Retention	1/30	21840271.9	m3	EWS	61338600.0	m2	502.4	5028.5	262.7
11	Retention	1/100	28590156.2	m3	-	0.0	-	657.6	6575.7	145.8
12	Retention	1/100	28590156.2	m3	EWS	61338600.0	m2	657.7	6580.9	112.3
13	Dry proofing	1/10	70976.5	m·building	-	0.0	-	38.4	768.0	924.6
14	Dry proofing	1/10	70976.5	m·building	EWS	61338600.0	m2	38.5	773.2	711.9
15	Dry proofing	1/30	75960.0	m·building	-	0.0	-	41.1	821.9	690.3
16	Dry proofing	1/30	75960.0	m·building	EWS	61338600.0	m2	41.2	827.1	531.5
17	Dry proofing	1/100	88516.5	m·building	-	0.0	-	47.9	957.7	533.4
18	Dry proofing	1/100	88516.5	m·building	EWS	61338600.0	m2	48.0	963.0	410.7
19	EWS	-	61338600.0	m2	-	0.0	-	0.1	5.2	5407.8

(e) Quantities and yearly cost/risk per measure strategy



(f) Overview of the input (inundation maps, land use map and damage functions)

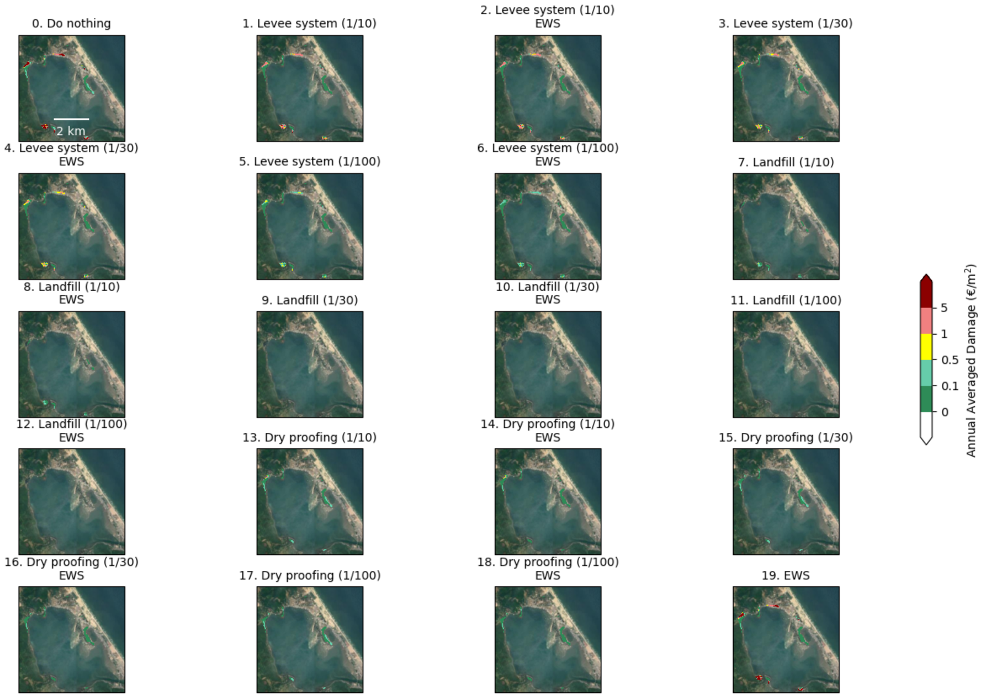


(g) Extents of the measures in the area

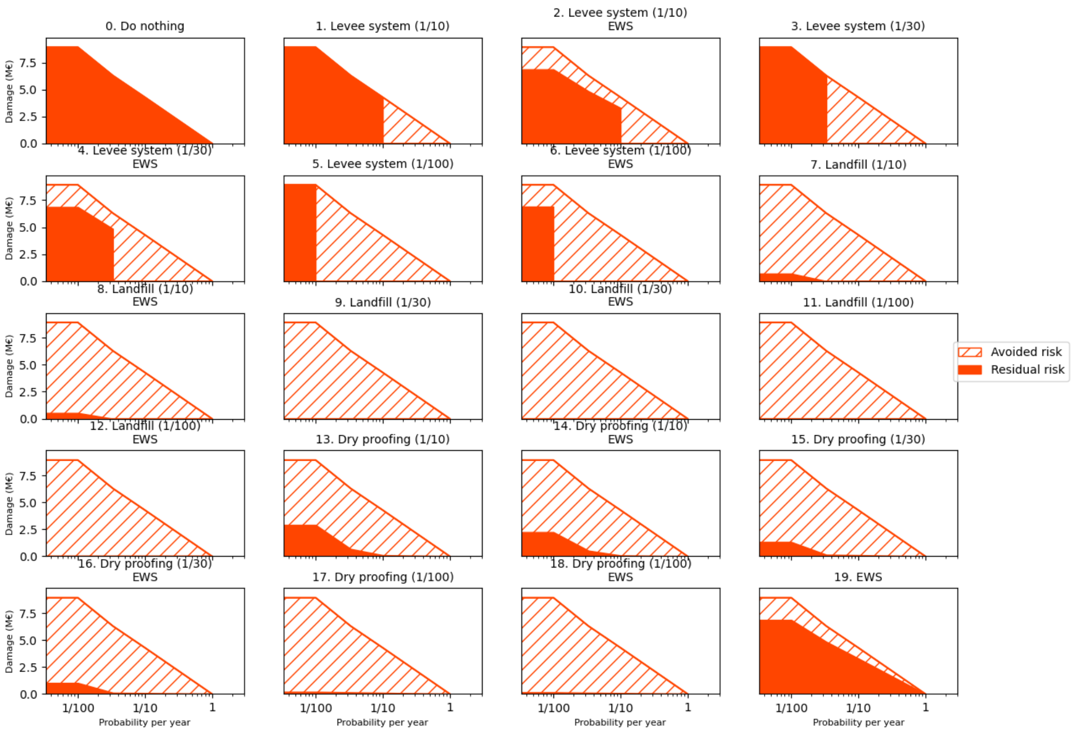
Figure A.2: Remaining part output framework for area 2

A.3. Area 3

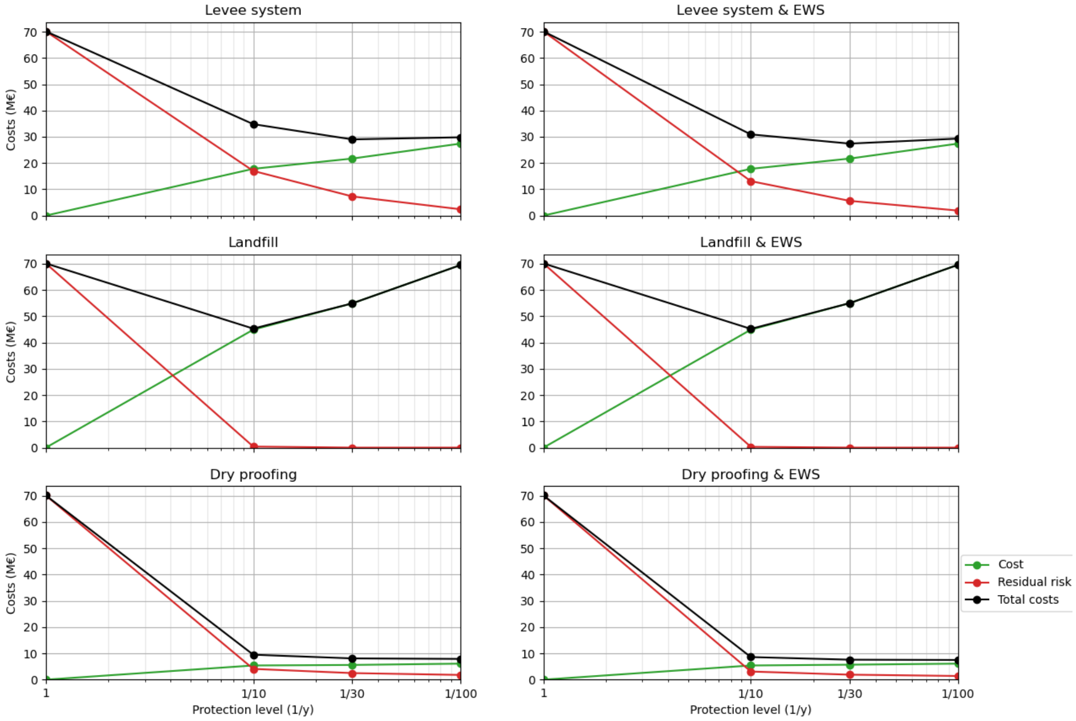
Area 3 is located in the southeast of the district and includes the Lap An lagoon. For this area, the selected measures were levee system, landfill, dry proofing and early warning system. The risk maps, damage graphs, cost graphs, NPV graph and quantity table can be found in Figures A.3a, A.3b, A.3c, A.3d and A.3e respectively. The background information is shown in Figures A.3f and A.3g. The calculation results are given in Section 4.3.



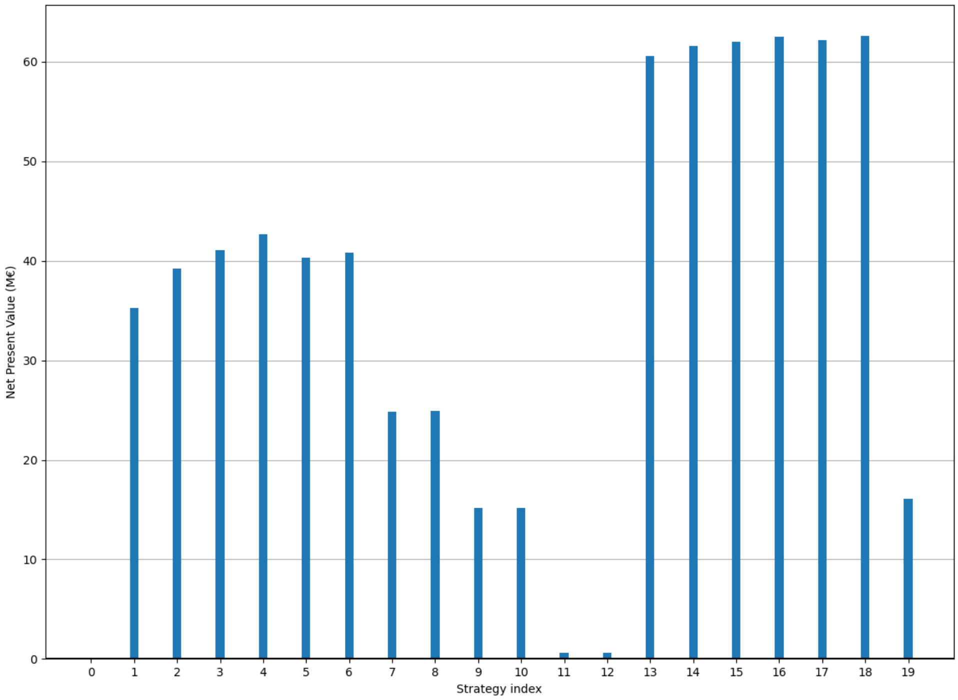
(a) Residual risk maps per measure strategy



(b) Damage graphs per measure strategy. On the horizontal axis is the probability per year and on the vertical axis is the direct economic damage.



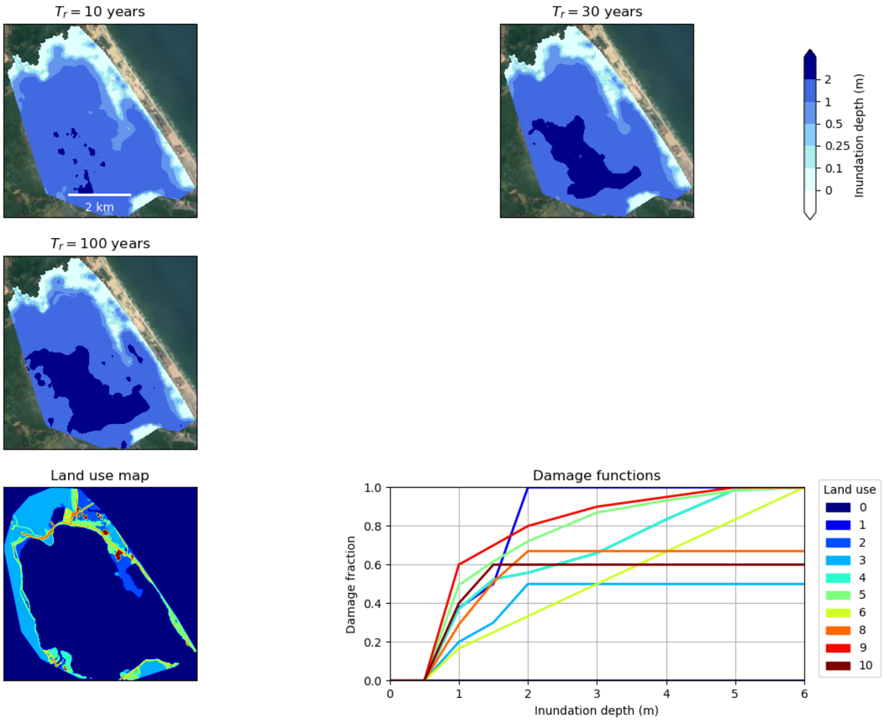
(c) Cost graphs per measure. On the horizontal axis is the design protection level and on the vertical axis is the cost.



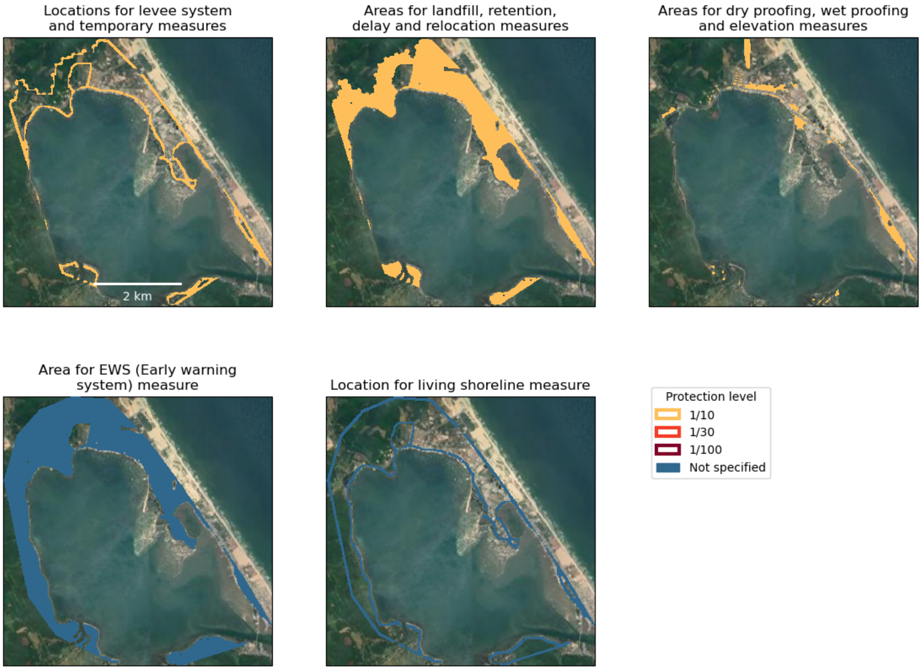
(d) Net present value graph. On the horizontal axis is the strategy index and on the vertical axis is the net present value.

	Measure 1	Protection level (1/y)	Quantity 1	Unit 1	Measure 2	Quantity 2	Unit 2	Investment (M€)	O&M (k€/y)	AAD (k€/y)
0	Do nothing	-	0.0	-	-	0.0	-	0.0	0.0	5093.6
1	Levee system	1/10	14424.6	m·m	-	0.0	-	17.3	34.6	1238.5
2	Levee system	1/10	14424.6	m·m	EWS	7675000.0	m2	17.3	35.3	953.6
3	Levee system	1/30	17600.3	m·m	-	0.0	-	21.1	42.2	533.5
4	Levee system	1/30	17600.3	m·m	EWS	7675000.0	m2	21.1	42.9	410.8
5	Levee system	1/100	22208.3	m·m	-	0.0	-	26.6	53.3	178.5
6	Levee system	1/100	22208.3	m·m	EWS	7675000.0	m2	26.7	54.0	137.4
7	Landfill	1/10	1747730.1	m·m2	-	0.0	-	43.7	87.4	30.1
8	Landfill	1/10	1747730.1	m·m2	EWS	7675000.0	m2	43.7	88.0	23.2
9	Landfill	1/30	2138745.3	m·m2	-	0.0	-	53.5	106.9	0.0
10	Landfill	1/30	2138745.3	m·m2	EWS	7675000.0	m2	53.5	107.6	0.0
11	Landfill	1/100	2706880.5	m·m2	-	0.0	-	67.7	135.3	0.0
12	Landfill	1/100	2706880.5	m·m2	EWS	7675000.0	m2	67.7	136.0	0.0
13	Dry proofing	1/10	7791.0	m·building	-	0.0	-	4.2	84.3	298.3
14	Dry proofing	1/10	7791.0	m·building	EWS	7675000.0	m2	4.2	85.0	229.7
15	Dry proofing	1/30	8167.0	m·building	-	0.0	-	4.4	88.4	181.5
16	Dry proofing	1/30	8167.0	m·building	EWS	7675000.0	m2	4.4	89.0	139.8
17	Dry proofing	1/100	8773.5	m·building	-	0.0	-	4.7	94.9	132.6
18	Dry proofing	1/100	8773.5	m·building	EWS	7675000.0	m2	4.8	95.6	102.1
19	EWS	-	7675000.0	m2	-	0.0	-	0.0	0.7	3922.1

(e) Quantities and yearly cost/risk per measure strategy



(f) Overview of the input (inundation maps, land use map and damage functions)



(g) Extents of the measures in the area

Figure A.3: Remaining part output framework for area 3

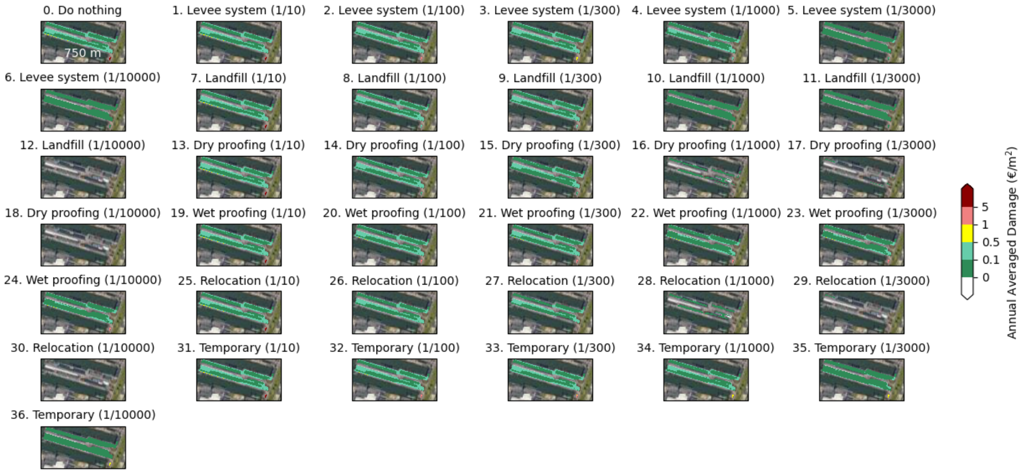
B

Framework output Waal Eemhaven

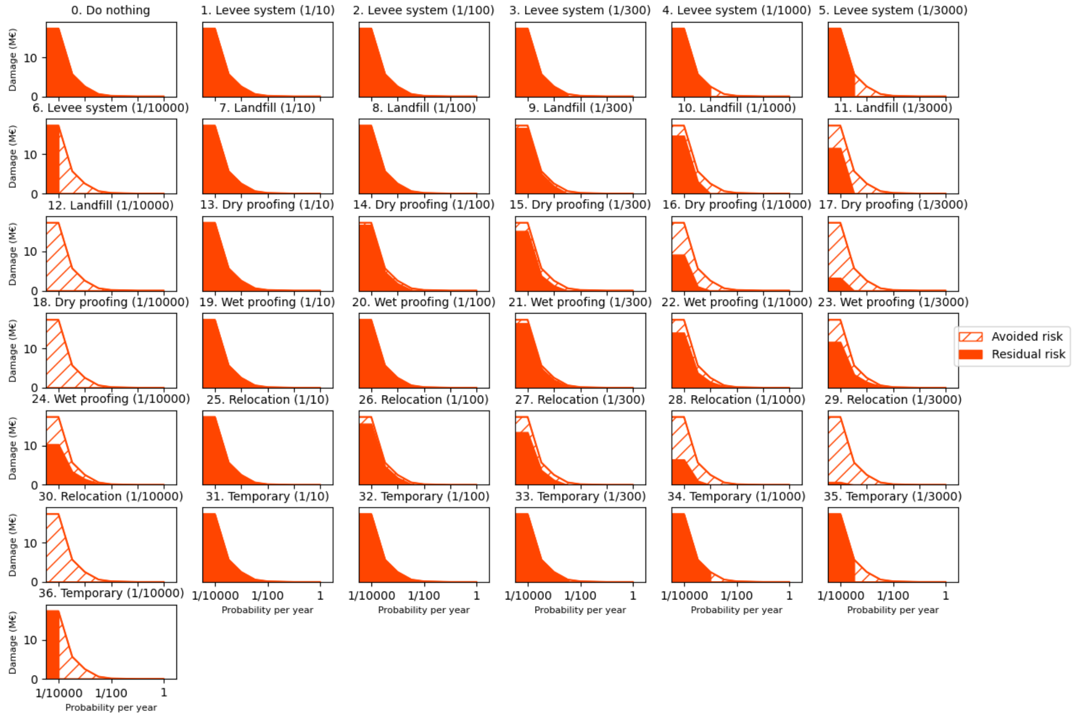
This appendix gives the framework's output for the Waal Eemhaven case study (Chapter 5). The simulations were done for three sub-areas: Pier 1, Pier 4 and Pier 6. These areas were also part of the report of Royal HaskoningDHV (2018a). The location of the sub-areas can be found in Figure 5.7. For all three sub-areas, the selected measures are relocation, levee system, landfill, dry proofing, wet proofing and temporary barrier. The calculation results are given in Section 5.3. The remaining part of the framework's output for Pier 1, 4 and 6 can be found in Sections B.1, B.2 and B.3 respectively.

B.1. Pier 1

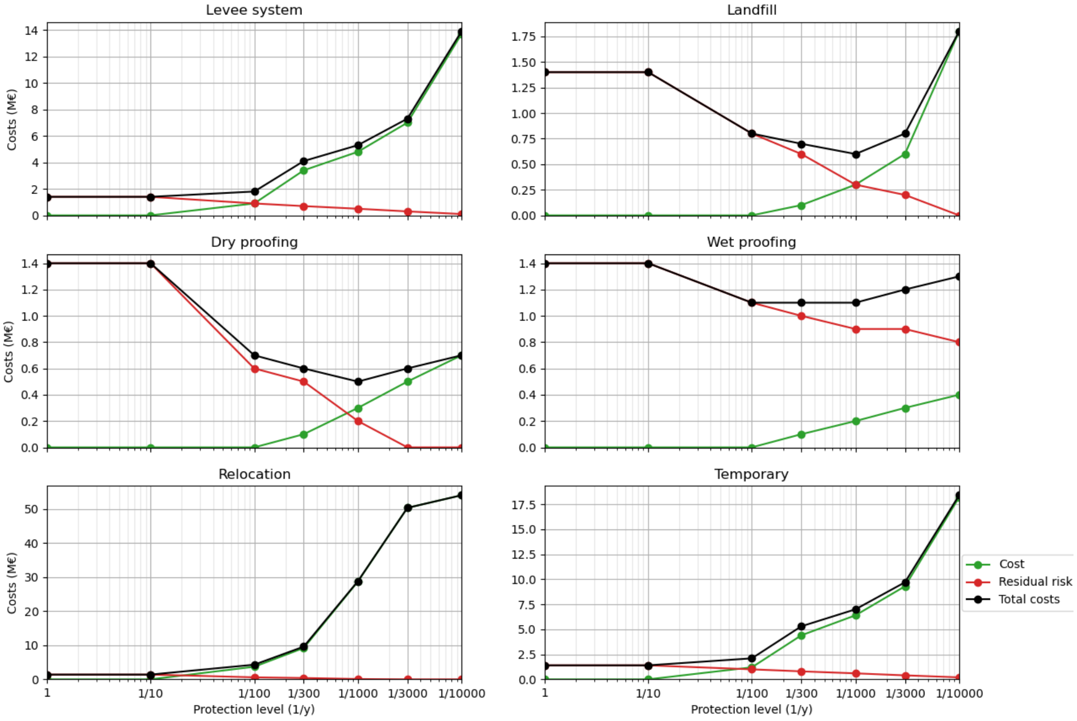
Pier 1 is located in the Northeast of the Waal Eemhaven. The selected measures are the same in all areas and are relocation, landfill, temporary barrier, dry proofing and wet proofing. The risk maps, damage graphs, cost graphs, NPV graph and quantities table can be found in Figures B.1a, B.1b, B.1c, B.1d and B.1e, respectively. The background information is shown in Figures B.1f and B.1g. The calculation results are given in Section 5.3.



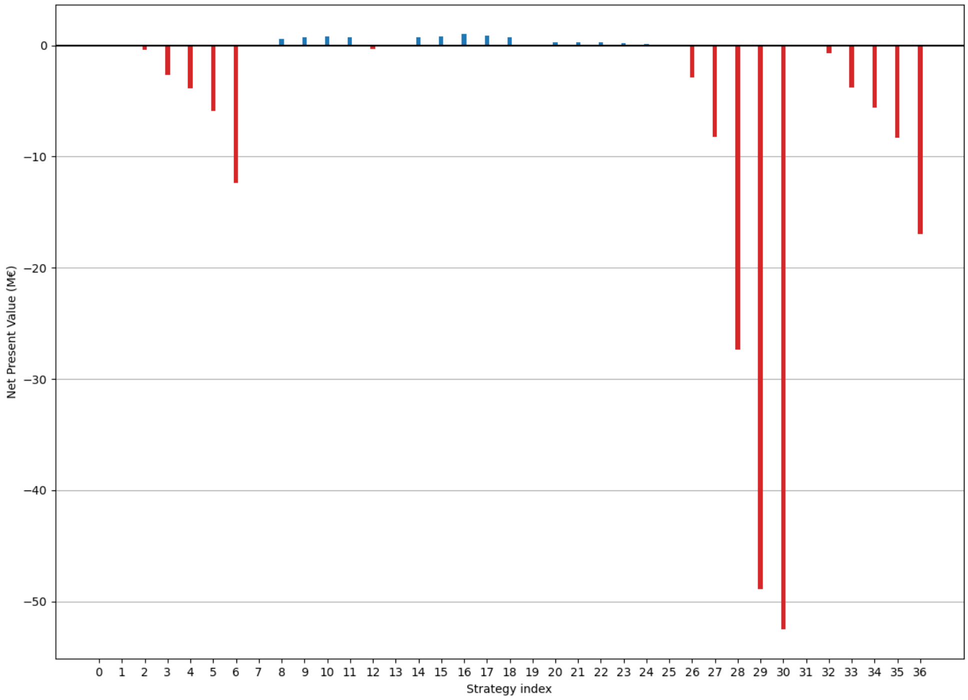
(a) Residual risk maps per measure strategy



(b) Damage graphs per measure strategy. On the horizontal axis is the probability per year and on the vertical axis is the direct economic damage.



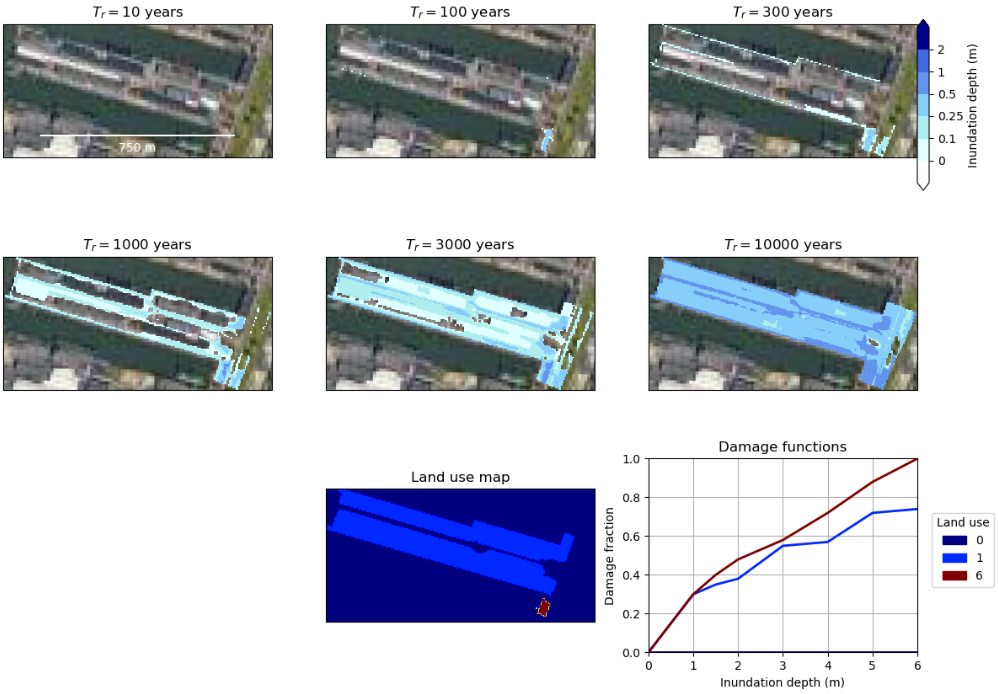
(c) Cost graphs per measure. On the horizontal axis is the design protection level and on the vertical axis is the cost.



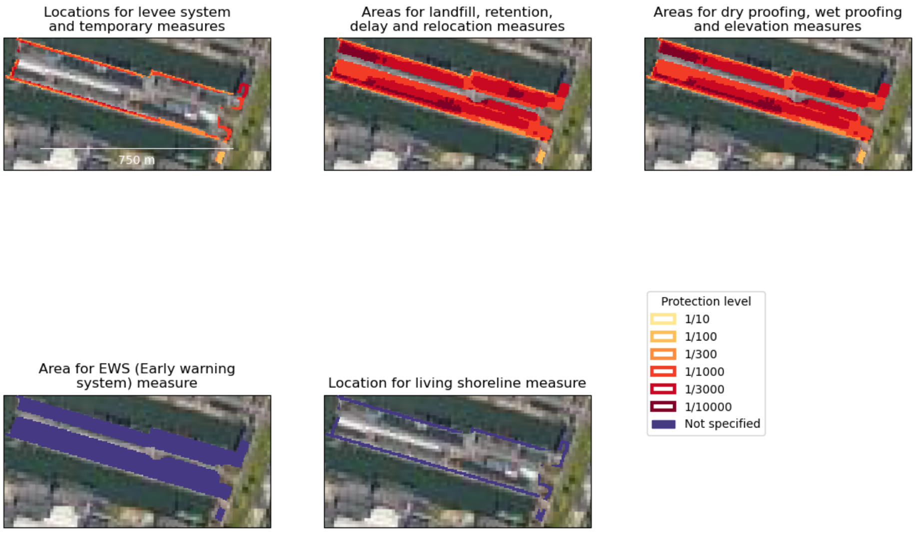
(d) Net present value graph. On the horizontal axis is the strategy index and on the vertical axis is the net present value.

	Measure 1	Protection level (1/y)	Quantity 1	Unit 1	Measure 2	Quantity 2	Unit 2	Investment (M€)	O&M (k€/y)	AAD (k€/y)
0	Do nothing	-	0.0	-	-	0	-	0.0	0.0	41.0
1	Levee system	1/10	0.0	m·m	-	0	-	0.0	0.0	41.0
2	Levee system	1/100	81.7	m·m	-	0	-	0.8	1.6	26.8
3	Levee system	1/300	313.6	m·m	-	0	-	3.1	6.3	21.7
4	Levee system	1/1000	450.9	m·m	-	0	-	4.5	9.0	14.3
5	Levee system	1/3000	653.7	m·m	-	0	-	6.5	13.1	8.8
6	Levee system	1/10000	1285.2	m·m	-	0	-	12.9	25.7	3.5
7	Landfill	1/10	0.0	m·m2	-	0	-	0.0	0.0	41.0
8	Landfill	1/100	695.9	m·m2	-	0	-	0.0	0.0	23.6
9	Landfill	1/300	2441.8	m·m2	-	0	-	0.1	0.1	17.6
10	Landfill	1/1000	9797.2	m·m2	-	0	-	0.2	0.5	9.2
11	Landfill	1/3000	21660.9	m·m2	-	0	-	0.5	1.1	5.0
12	Landfill	1/10000	65609.5	m·m2	-	0	-	1.6	3.3	0.0
13	Dry proofing	1/10	0.0	m·building	-	0	-	0.0	0.0	41.0
14	Dry proofing	1/100	2.5	m·building	-	0	-	0.0	0.4	19.0
15	Dry proofing	1/300	6.3	m·building	-	0	-	0.1	1.1	13.9
16	Dry proofing	1/1000	19.7	m·building	-	0	-	0.2	3.4	5.0
17	Dry proofing	1/3000	34.7	m·building	-	0	-	0.3	6.0	1.4
18	Dry proofing	1/10000	46.7	m·building	-	0	-	0.4	8.1	0.0
19	Wet proofing	1/10	0.0	m·building	-	0	-	0.0	0.0	41.0
20	Wet proofing	1/100	2.5	m·building	-	0	-	0.0	0.3	32.2
21	Wet proofing	1/300	6.3	m·building	-	0	-	0.0	0.7	30.2
22	Wet proofing	1/1000	19.7	m·building	-	0	-	0.1	2.1	26.6
23	Wet proofing	1/3000	34.7	m·building	-	0	-	0.2	3.7	25.2
24	Wet proofing	1/10000	46.7	m·building	-	0	-	0.2	5.0	24.6
25	Relocation	1/10	0.0	m2	-	0	-	0.0	0.0	41.0
26	Relocation	1/100	10100.0	m2	-	0	-	3.6	3.6	18.4
27	Relocation	1/300	25025.0	m2	-	0	-	8.9	8.9	13.1
28	Relocation	1/1000	78400.0	m2	-	0	-	27.8	27.8	3.8
29	Relocation	1/3000	137325.0	m2	-	0	-	48.6	48.6	0.3
30	Relocation	1/10000	147325.0	m2	-	0	-	52.2	52.2	0.0
31	Temporary	1/10	0.0	m·m	-	0	-	0.0	0.0	41.0
32	Temporary	1/100	81.7	m·m	-	0	-	0.4	21.2	28.2
33	Temporary	1/300	313.6	m·m	-	0	-	1.6	81.5	23.6
34	Temporary	1/1000	450.9	m·m	-	0	-	2.3	117.2	17.0
35	Temporary	1/3000	653.7	m·m	-	0	-	3.4	170.0	12.1
36	Temporary	1/10000	1285.2	m·m	-	0	-	6.7	334.2	7.2

(e) Quantities and yearly cost/risk per measure strategy



(f) Overview of the input (inundation maps, land use map and damage functions)

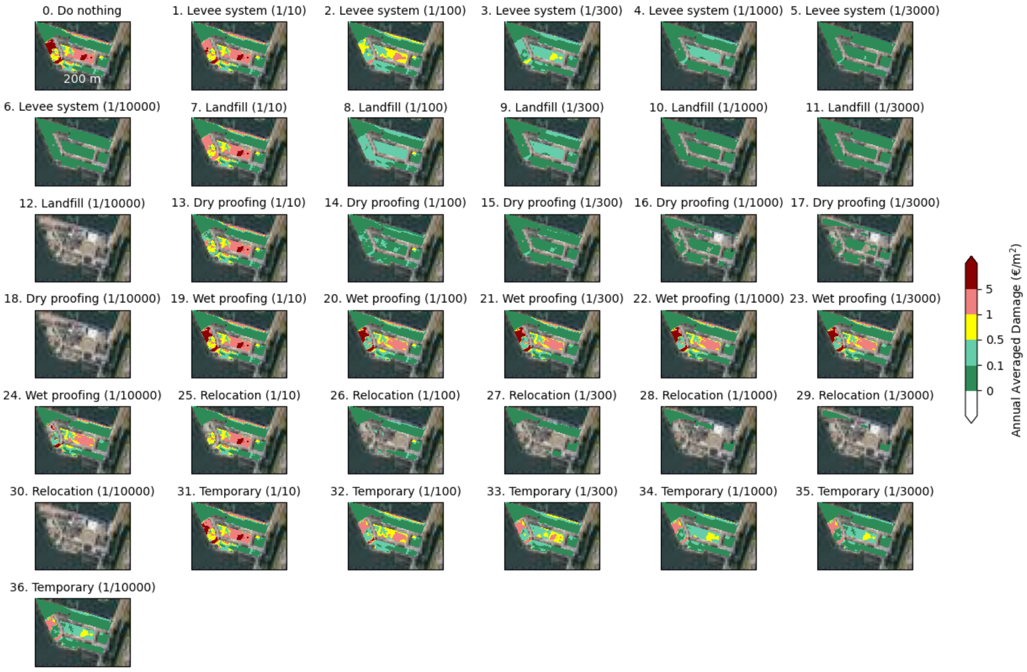


(g) Extents of the measures in the area

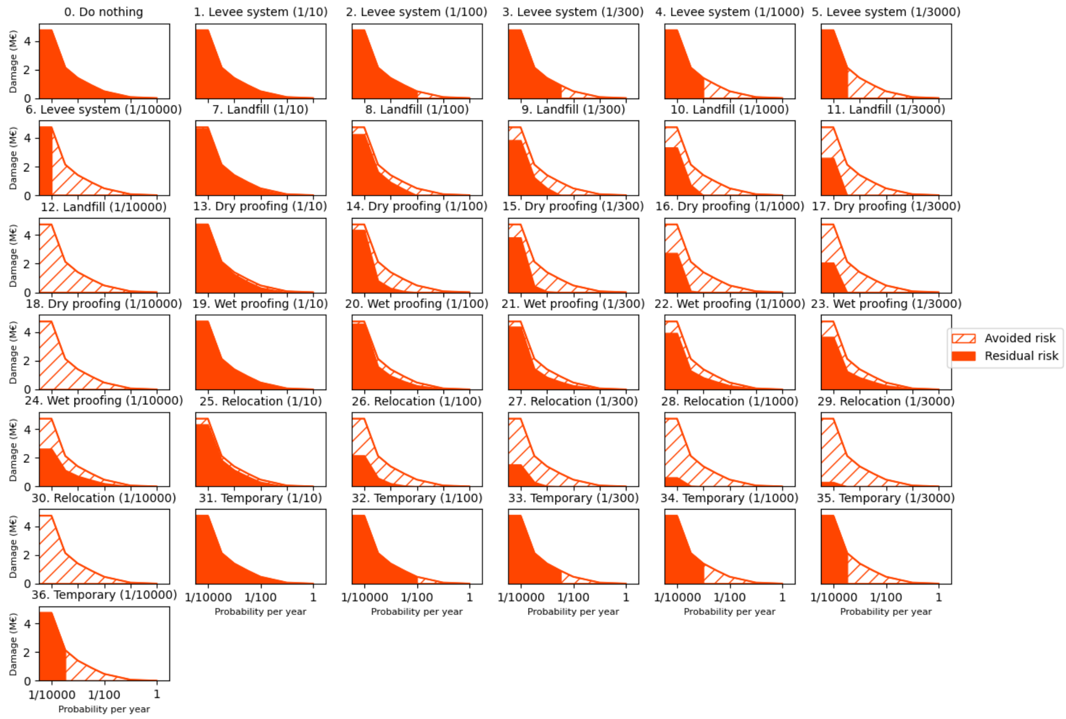
Figure B.1: Remaining part output framework for Pier 1

B.2. Pier 4

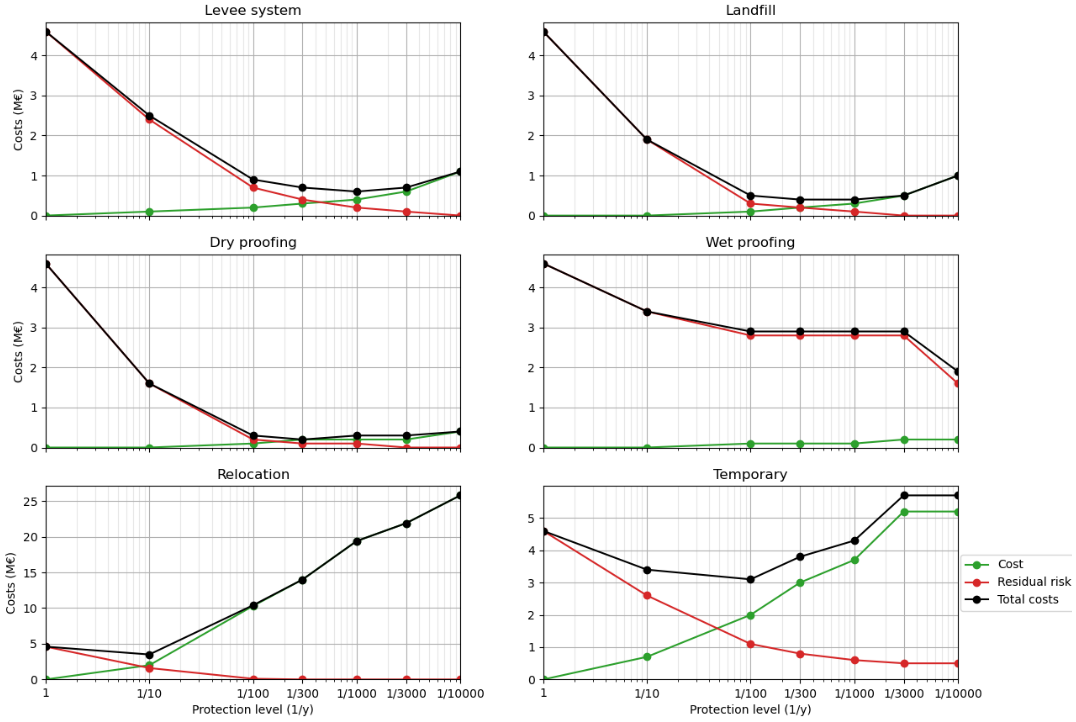
The second sub-area is Pier 4 and is located in the Southeast of the Waal Eemhaven. It is the smallest selected sub-area in the Waal Eemhaven. The framework's output, containing the risk maps, damage graphs, cost graphs, NPV graph and quantity table can be found in Figures B.2a, B.2b, B.2c, B.2d and B.2e respectively. The background information is shown in Figures B.2f and B.2g. The calculation results are given in Section 5.3. Note that the uncertainty analysis is not included, as mentioned in Section 5.1.



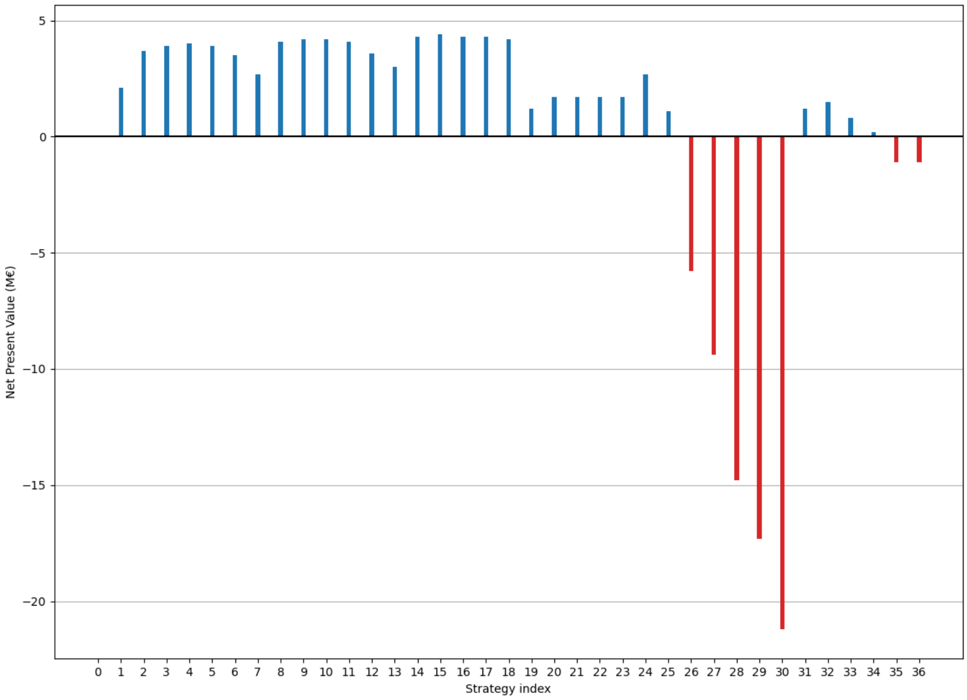
(a) Residual risk maps per measure strategy



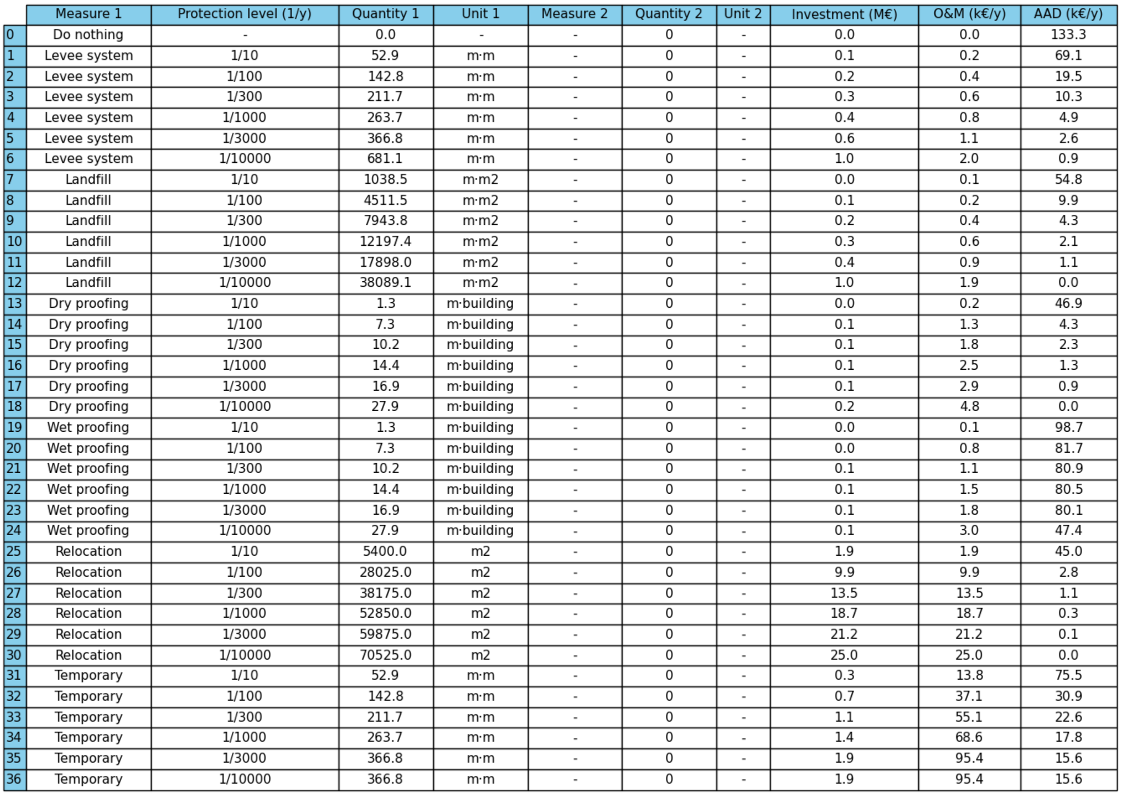
(b) Damage graphs per measure strategy. On the horizontal axis is the probability per year and on the vertical axis is the direct economic damage.



(c) Cost graphs per measure. On the horizontal axis is the design protection level and on the vertical axis is the cost.

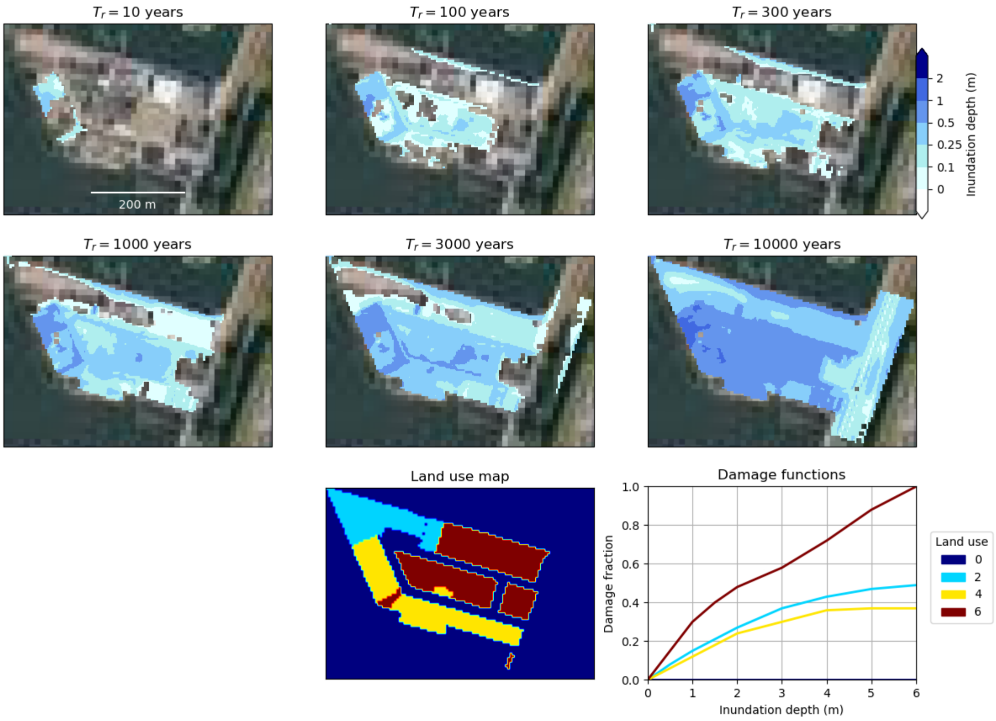


(d) Net present value graph. On the horizontal axis is the strategy index and on the vertical axis is the net present value.

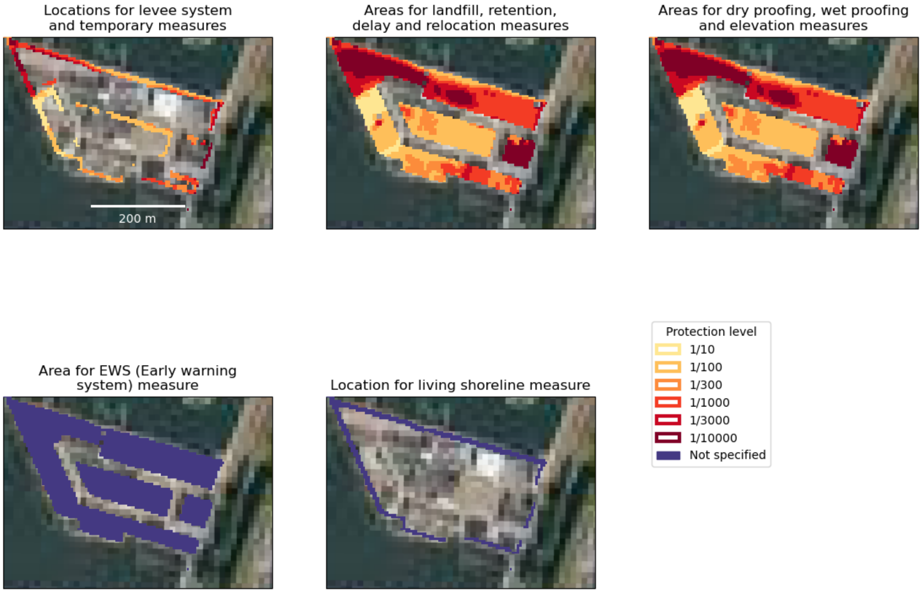


	Measure 1	Protection level (1/y)	Quantity 1	Unit 1	Measure 2	Quantity 2	Unit 2	Investment (M€)	O&M (k€/y)	AAD (k€/y)
0	Do nothing	-	0.0	-	-	0	-	0.0	0.0	133.3
1	Levee system	1/10	52.9	m·m	-	0	-	0.1	0.2	69.1
2	Levee system	1/100	142.8	m·m	-	0	-	0.2	0.4	19.5
3	Levee system	1/300	211.7	m·m	-	0	-	0.3	0.6	10.3
4	Levee system	1/1000	263.7	m·m	-	0	-	0.4	0.8	4.9
5	Levee system	1/3000	366.8	m·m	-	0	-	0.6	1.1	2.6
6	Levee system	1/10000	681.1	m·m	-	0	-	1.0	2.0	0.9
7	Landfill	1/10	1038.5	m·m2	-	0	-	0.0	0.1	54.8
8	Landfill	1/100	4511.5	m·m2	-	0	-	0.1	0.2	9.9
9	Landfill	1/300	7943.8	m·m2	-	0	-	0.2	0.4	4.3
10	Landfill	1/1000	12197.4	m·m2	-	0	-	0.3	0.6	2.1
11	Landfill	1/3000	17898.0	m·m2	-	0	-	0.4	0.9	1.1
12	Landfill	1/10000	38089.1	m·m2	-	0	-	1.0	1.9	0.0
13	Dry proofing	1/10	1.3	m·building	-	0	-	0.0	0.2	46.9
14	Dry proofing	1/100	7.3	m·building	-	0	-	0.1	1.3	4.3
15	Dry proofing	1/300	10.2	m·building	-	0	-	0.1	1.8	2.3
16	Dry proofing	1/1000	14.4	m·building	-	0	-	0.1	2.5	1.3
17	Dry proofing	1/3000	16.9	m·building	-	0	-	0.1	2.9	0.9
18	Dry proofing	1/10000	27.9	m·building	-	0	-	0.2	4.8	0.0
19	Wet proofing	1/10	1.3	m·building	-	0	-	0.0	0.1	98.7
20	Wet proofing	1/100	7.3	m·building	-	0	-	0.0	0.8	81.7
21	Wet proofing	1/300	10.2	m·building	-	0	-	0.1	1.1	80.9
22	Wet proofing	1/1000	14.4	m·building	-	0	-	0.1	1.5	80.5
23	Wet proofing	1/3000	16.9	m·building	-	0	-	0.1	1.8	80.1
24	Wet proofing	1/10000	27.9	m·building	-	0	-	0.1	3.0	47.4
25	Relocation	1/10	5400.0	m2	-	0	-	1.9	1.9	45.0
26	Relocation	1/100	28025.0	m2	-	0	-	9.9	9.9	2.8
27	Relocation	1/300	38175.0	m2	-	0	-	13.5	13.5	1.1
28	Relocation	1/1000	52850.0	m2	-	0	-	18.7	18.7	0.3
29	Relocation	1/3000	59875.0	m2	-	0	-	21.2	21.2	0.1
30	Relocation	1/10000	70525.0	m2	-	0	-	25.0	25.0	0.0
31	Temporary	1/10	52.9	m·m	-	0	-	0.3	13.8	75.5
32	Temporary	1/100	142.8	m·m	-	0	-	0.7	37.1	30.9
33	Temporary	1/300	211.7	m·m	-	0	-	1.1	55.1	22.6
34	Temporary	1/1000	263.7	m·m	-	0	-	1.4	68.6	17.8
35	Temporary	1/3000	366.8	m·m	-	0	-	1.9	95.4	15.6
36	Temporary	1/10000	366.8	m·m	-	0	-	1.9	95.4	15.6

(e) Quantities and yearly cost/risk per measure strategy



(f) Overview of the input (inundation maps, land use map and damage functions)

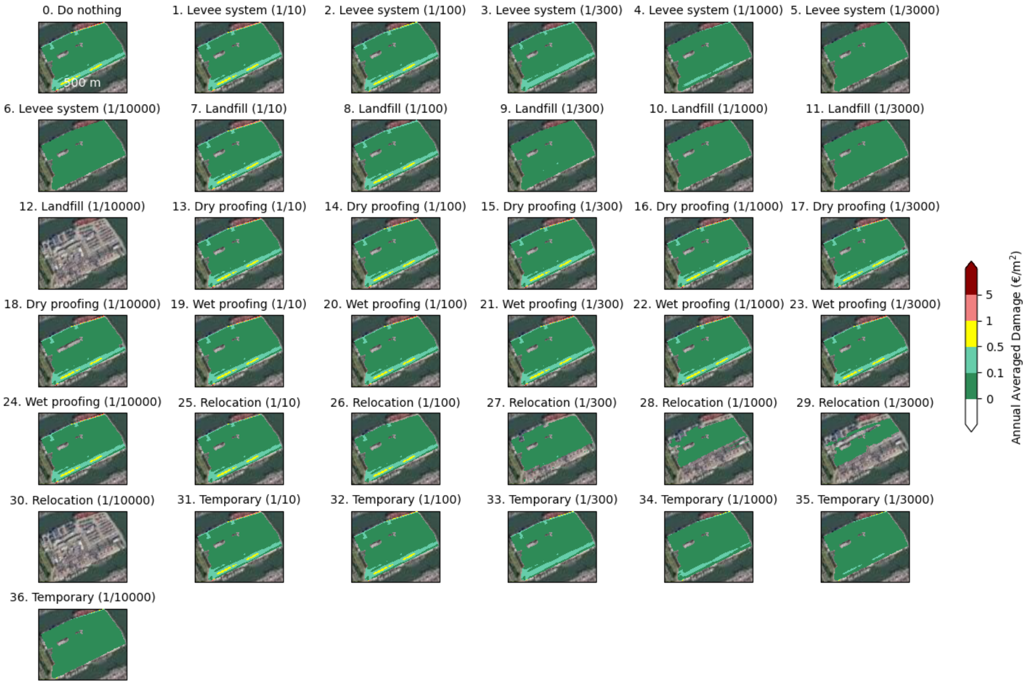


(g) Extents of the measures in the area

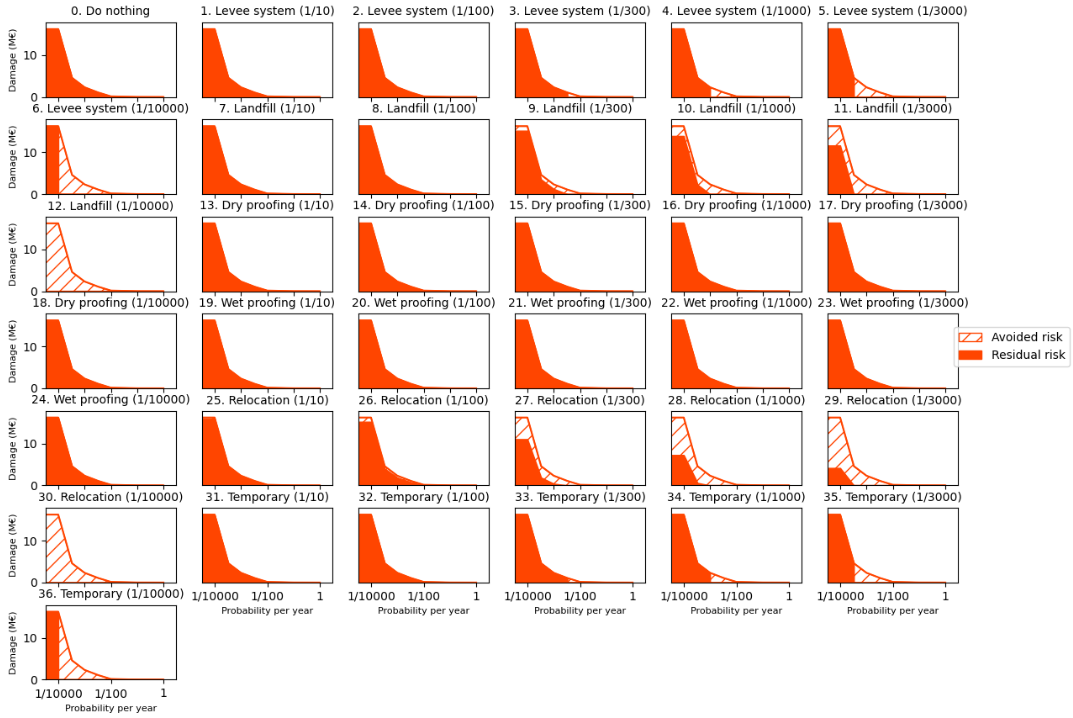
Figure B.2: Remaining part output framework for Pier 4

B.3. Pier 6

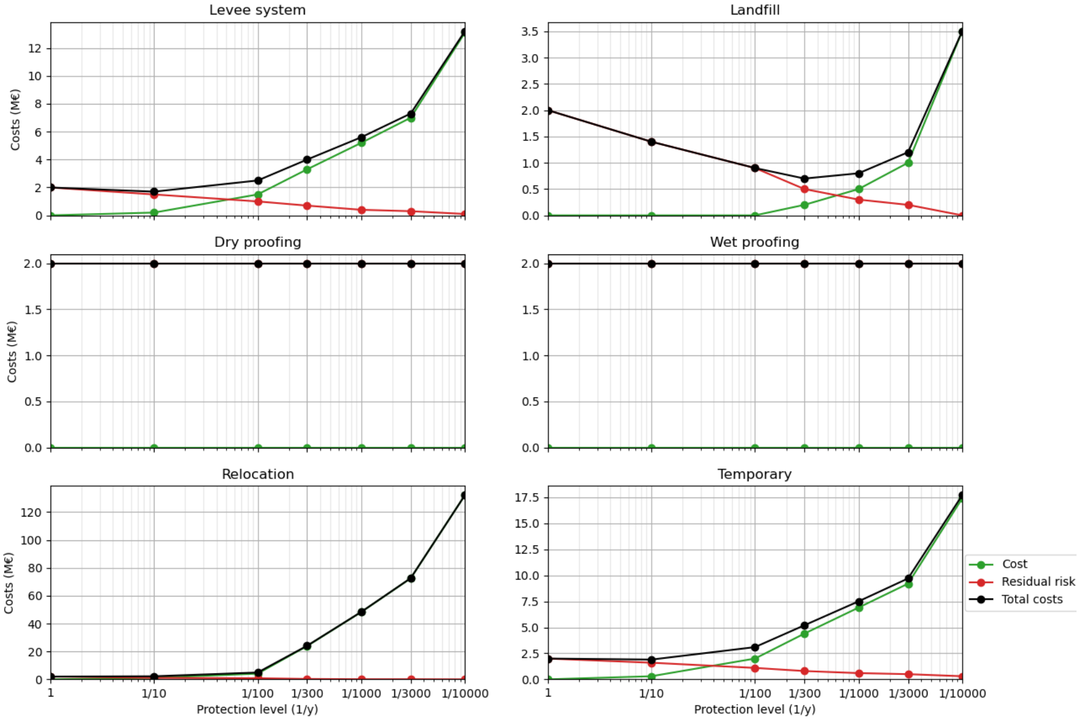
Pier 6 is located in the North of the Waal Eemhaven and is the largest selected sub-area in the Waal Eemhaven. The framework's output, containing the risk maps, damage graphs, cost graphs, NPV graph and quantity table can be found in Figures B.3a, B.3b, B.3c, B.3d and B.3e respectively. The background information is shown in Figures B.3f and B.3g. The calculation results are given in Section 5.3.



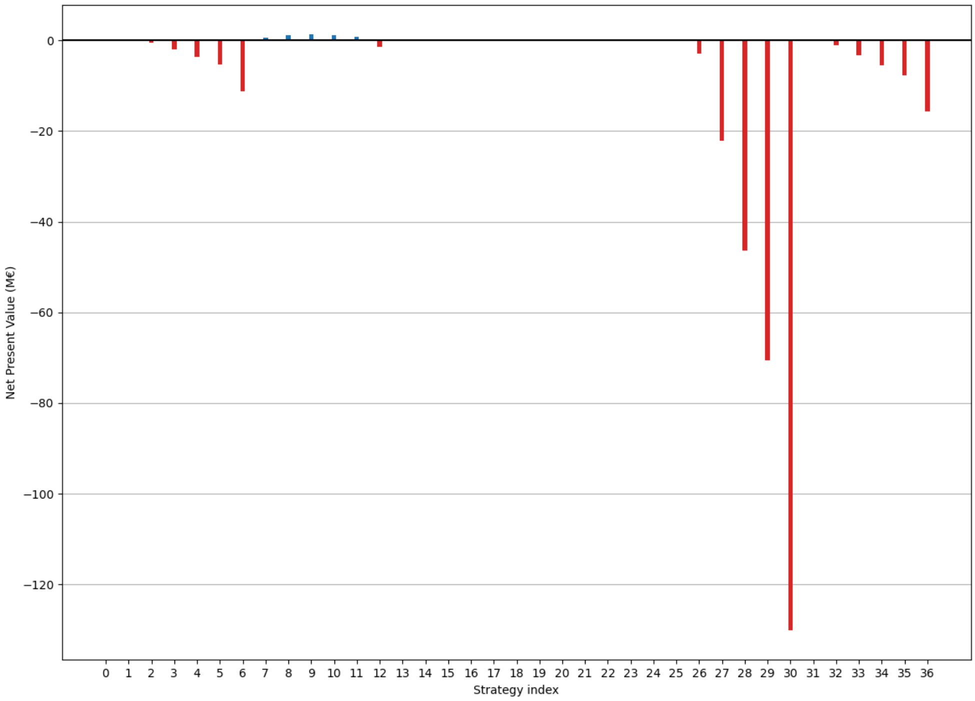
(a) Residual risk maps per measure strategy



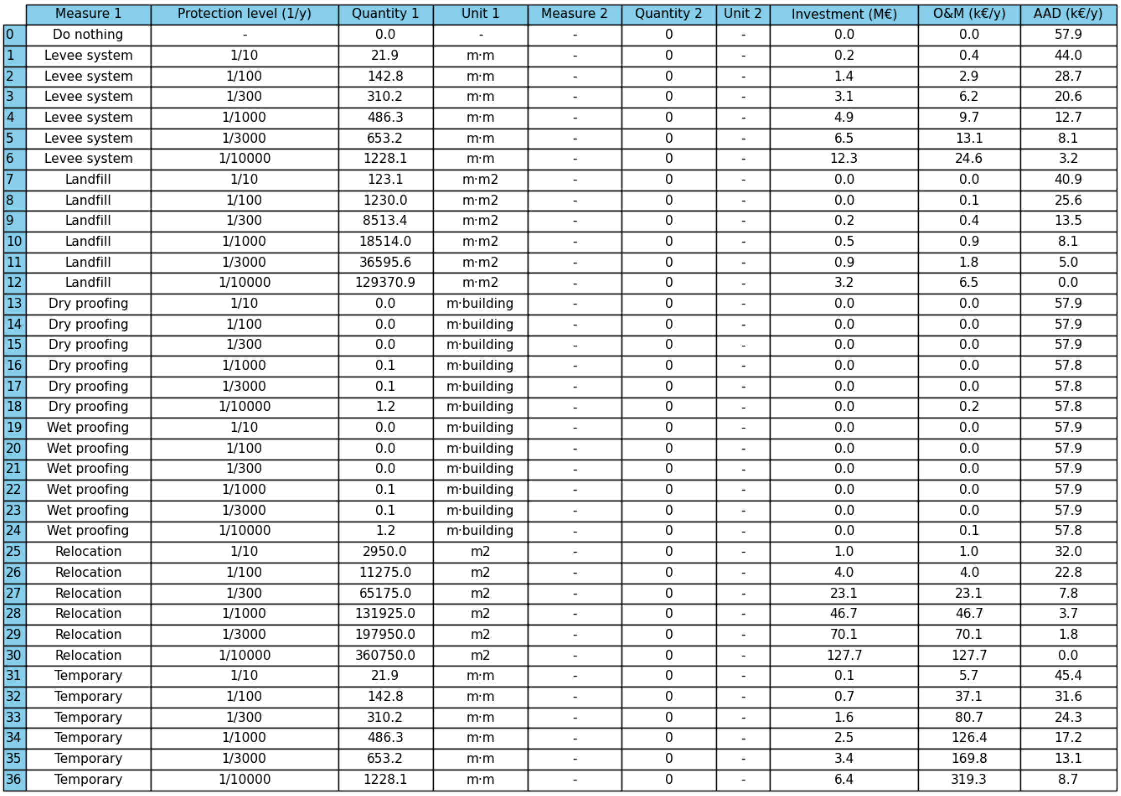
(b) Damage graphs per measure strategy. On the horizontal axis is the probability per year and on the vertical axis is the direct economic damage.



(c) Cost graphs per measure. On the horizontal axis is the design protection level and on the vertical axis is the cost.

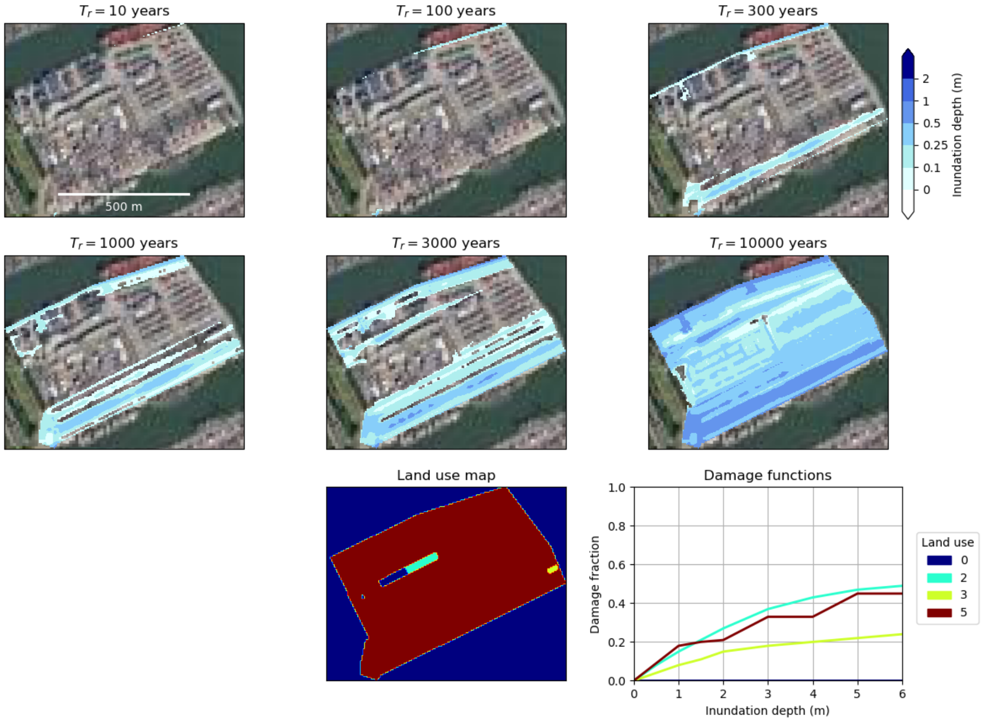


(d) Net present value graph. On the horizontal axis is the strategy index and on the vertical axis is the net present value.

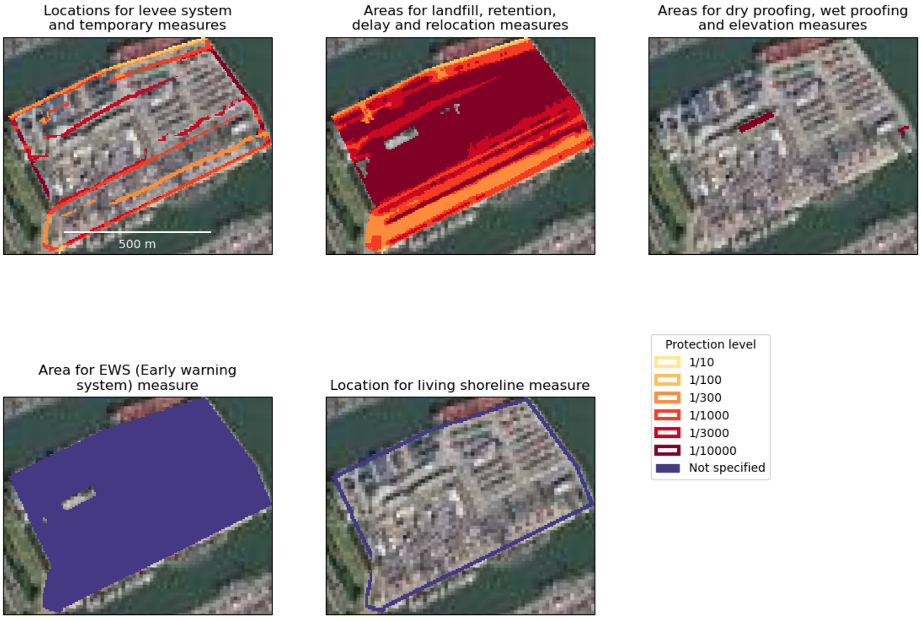


	Measure 1	Protection level (1/y)	Quantity 1	Unit 1	Measure 2	Quantity 2	Unit 2	Investment (M€)	O&M (k€/y)	AAD (k€/y)
0	Do nothing	-	0.0	-	-	0	-	0.0	0.0	57.9
1	Levee system	1/10	21.9	m·m	-	0	-	0.2	0.4	44.0
2	Levee system	1/100	142.8	m·m	-	0	-	1.4	2.9	28.7
3	Levee system	1/300	310.2	m·m	-	0	-	3.1	6.2	20.6
4	Levee system	1/1000	486.3	m·m	-	0	-	4.9	9.7	12.7
5	Levee system	1/3000	653.2	m·m	-	0	-	6.5	13.1	8.1
6	Levee system	1/10000	1228.1	m·m	-	0	-	12.3	24.6	3.2
7	Landfill	1/10	123.1	m·m2	-	0	-	0.0	0.0	40.9
8	Landfill	1/100	1230.0	m·m2	-	0	-	0.0	0.1	25.6
9	Landfill	1/300	8513.4	m·m2	-	0	-	0.2	0.4	13.5
10	Landfill	1/1000	18514.0	m·m2	-	0	-	0.5	0.9	8.1
11	Landfill	1/3000	36595.6	m·m2	-	0	-	0.9	1.8	5.0
12	Landfill	1/10000	129370.9	m·m2	-	0	-	3.2	6.5	0.0
13	Dry proofing	1/10	0.0	m·building	-	0	-	0.0	0.0	57.9
14	Dry proofing	1/100	0.0	m·building	-	0	-	0.0	0.0	57.9
15	Dry proofing	1/300	0.0	m·building	-	0	-	0.0	0.0	57.9
16	Dry proofing	1/1000	0.1	m·building	-	0	-	0.0	0.0	57.8
17	Dry proofing	1/3000	0.1	m·building	-	0	-	0.0	0.0	57.8
18	Dry proofing	1/10000	1.2	m·building	-	0	-	0.0	0.2	57.8
19	Wet proofing	1/10	0.0	m·building	-	0	-	0.0	0.0	57.9
20	Wet proofing	1/100	0.0	m·building	-	0	-	0.0	0.0	57.9
21	Wet proofing	1/300	0.0	m·building	-	0	-	0.0	0.0	57.9
22	Wet proofing	1/1000	0.1	m·building	-	0	-	0.0	0.0	57.9
23	Wet proofing	1/3000	0.1	m·building	-	0	-	0.0	0.0	57.9
24	Wet proofing	1/10000	1.2	m·building	-	0	-	0.0	0.1	57.8
25	Relocation	1/10	2950.0	m2	-	0	-	1.0	1.0	32.0
26	Relocation	1/100	11275.0	m2	-	0	-	4.0	4.0	22.8
27	Relocation	1/300	65175.0	m2	-	0	-	23.1	23.1	7.8
28	Relocation	1/1000	131925.0	m2	-	0	-	46.7	46.7	3.7
29	Relocation	1/3000	197950.0	m2	-	0	-	70.1	70.1	1.8
30	Relocation	1/10000	360750.0	m2	-	0	-	127.7	127.7	0.0
31	Temporary	1/10	21.9	m·m	-	0	-	0.1	5.7	45.4
32	Temporary	1/100	142.8	m·m	-	0	-	0.7	37.1	31.6
33	Temporary	1/300	310.2	m·m	-	0	-	1.6	80.7	24.3
34	Temporary	1/1000	486.3	m·m	-	0	-	2.5	126.4	17.2
35	Temporary	1/3000	653.2	m·m	-	0	-	3.4	169.8	13.1
36	Temporary	1/10000	1228.1	m·m	-	0	-	6.4	319.3	8.7

(e) Quantities and yearly cost/risk per measure strategy



(f) Overview of the input (inundation maps, land use map and damage functions)



(g) Extents of the measures in the area

Figure B.3: Remaining part output framework for Pier 6