Gelderland: Mitigating the flood risk of the Ijssel river

An exploratory modeling approach in a challenging political arena

Student Group	**20**
Anmol Soni	5290228
Elie Azeufack	5231000
Lekha Nambiar	5200512
Marco Peretto	5366240
Roel Diegens	5432529
Ziad Matar	4670981

TU Delft

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Executive Summary

In the last decades, the Ijssel River has been posing an ever-growing threat to the people living in the Gelderland Province. The previously mentioned river has been prone to floods in recent times, making it necessary for the region to come up with a solid plan to combat such a phenomenon. The province of Gelderland needs to find a policy protecting its citizens but acceptable for other stakeholders in the political arena as it will be subjected to voting. This task is quite complex, as the policies available for each actor are numerous and the river system studied is complex. Moreover, the unpredictable nature of climate change further increases the complexity of the problem.

It must be kept in mind that human lives are at stake, in this case, reducing the room for error virtually to zero. Within such analysis, several modeling techniques can be used, following a pre-delineated procedure. However, as with every socio-technical problem, several actors or stakeholders are in play and the desires of every single one of these have to be taken into account. The Ijssel River flows through different provinces and towns. Thus, different municipalities and provinces will have to interact with each other and be considered within the broader actor arena. Not to mention other stakeholders strictly related to more technical aspects, such as the Rijkswaterstraat. Maintaining good relations and cooperation within all the actors is of critical importance, as without it, no practical solution to the problem at hand can be found.

An advanced simulation was performed to guide decision-makers in Gelderland. The Exploratory Modelling Analysis python workbench offers algorithms designed specifically for such purposes. Three policy levers to the flooding problem are available, namely: dike heightening, an early alarm system implementation, or creating room for the river. Each policy comes with different consequences, ranging from economic costs to physical damages. In order to simulate every different scenario resulting from different combinations of parameters, and taking into account deep uncertainty, several modeling approaches were utilized.

An optimal policy that can be implemented in three planning cycles was formulated. In the first planning cycle, a combination of room for river and dike heightening measures are proposed. Indeed, room for the river should be created in Tichelbeekse Waard and Welsummer buitenwaarden. Additionally, dike heightening by 6 decimeters in Doesburg, 7 decimeters in Cortenoever, 7 decimeters in Zutphen, 6 decimeters in Gorssel, and 3 decimeters in Deventer is also recommended. In a second step, dike heightening at Zutphen, Gorssel, and Deventer by 7 decimeters, 6 decimeters, and 1 decimeter respectively, is advised. Lastly in the third phase of the planning cycle, the last round of dike heightening at Zutphen, Gorssel, and Deventer by 7 decimeters, 7 decimeters, and 4 decimeters respectively is proposed.

Considering that the flood mitigation measures are funded by Rijskwaterstraat, the main challenge for the province of Gelderland when it comes to implementing the proposed policy is to convince other actors to appropriately compensate the displacement of its citizens caused by the room for the river project. In order to navigate this complex political arena, an extensive political reflection is provided.

1

Problem Framing

With its historical roots dating back to the Holy Roman Empire, Gelderland has always relied on its access to both the North Sea and three main rivers located inside its area, these namely being: the Rhine, the Maas, and the Ijssel. The following report will focus on the latter, more precisely elaborating on the different aspects involved when delineating a flood mitigation plan to counter it. In fact, with climate change posing an ever-greater threat to the province (and the Netherlands as a whole) (Field et al. (2012)), it is vital to mitigate the ongoing expansion of the river. In order to do this, an Exploratory Modelling Analysis (EMA) will be carried out. This entails the usage of specific workbenches and algorithms carefully designed to consider a multitude of parameters and scenarios and processing results according to different combinations of these. In addition, a section devoted to the political reflection related to the interaction of different stakeholders present in the problem at hand will be presented.

1.1. Flooding risk in the Ijssel river: potential damages, tensions, and water management

The Ijssel River can be subdivided into five distinct dike rings. These are: Doesburg (Dike 1), Cortenoever (Dike 2), Zutphen (Dike 3), Gorssel (Dike 4) and Deventer (Dike 5). This report will focus on the first three dikes, as these are part of the Gelderland Province whereas the rest are part of the Overijssel Province. These rings are important points of the river where its water levels can be deeply studied, analyzed, and monitored. Following the two near flood situations that happened in succession at the end of the last century (Field et al. (2012)), flood monitoring has gained even higher concerns than it already had due to climate change. In fact, after the two succeeding undesirable events, a new plan for countering such problems was delineated, namely the “Room for the River” project. The previously mentioned project included 34 different projects tackling flooding of rivers throughout the Netherlands that were all concluded in 2015 (Zevenbergen et al. (2013)). The flooding of rivers would not only entail economic losses but potentially also human losses. Due to the historical underpinnings related to building settlements next to rivers, even nowadays big urban centers can be found next to the rivers. Hence, the vital importance of the problem at hand.

1.2. Stakeholder analysis: Context setters, players, subjects, and the crowd

To design an efficient policy that minimizes the costs and the risks inflicted on Gelderland citizens, it is necessary to understand the political arena where the decision-making is made. Indeed, mapping out the stakeholders involved and their interrelations allows the province's representatives to smoothly navigate the political arena. To illustrate the interrelations of the different actors, a Mendelow diagram is used: stakeholders are classified into four categories on the basis of a power-interest matrix.

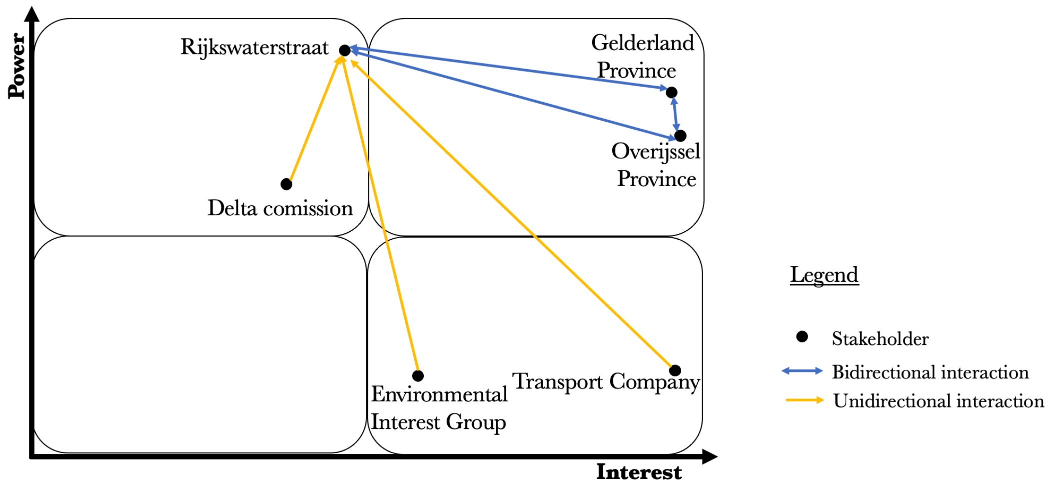


Figure 1.1: Mendelow Diagram.

As it can be seen in Figure 1.1, Rijkswaterstraat is a central actor which is in contact with most stakeholders. From the diagram, it is possible to divide stakeholders into three categories. The provinces of Gelderland and Overijssel are key players because they have very high power and interest: indeed, they can shape policies and would directly suffer the consequences of a flood. The province of Gelderland has leverage over the province of Overijssel because, being located upstream, the policies of Gelderland affect Overijssel, which is located downstream. Possessing a relatively lower interest but high power, Rijkswaterstraat, and the Delta commission are classified as context setters. These two stakeholders define the possibilities and the boundaries of this water management project as a whole. These actors have many projects under their supervision, which is why their interest is lower than that of the concerned provinces. The Environmental Interest Group and the Transport company have a high interest in the project but have very little power to sway this complex decision-making process. Thus, they can be categorized as subjects.

Although the municipalities play an important role in shaping the policy, they are not included in this diagram, which aims to give a general overview of the political arena. They communicate their concerns to their respective provinces and are represented by them. More information regarding the municipalities is available in Table 1.1.

Stakeholder	Perceptions, Powers and Interests
Rijkswaterstaat	This is the executive branch of the Dutch Ministry of Infrastructure and Water Management with mainly administrative powers. Their main role is to resolve all possible flood-related conflicts along the river. For this, they organize a debate in the decision arena in which each actor presents its views, interests, and preferred policies and engage in serious discussions. In the end, the Rikswaterstaat develops a policy based on all those interests and presents it to the Delta Commission after a vote for funding (Kwakkel (2021)). According to the National Delta program 2021 report (Postma and de Wit (2021)), the main objective of the Rijkswaterstaat, within the frame of the “Dutch National Flood reduction programme” is to have all primary flood defense systems meet the minimum standards by 2050. This implies for every person residing behind a primary dike, achieving a minimum protection level of 1 in 100,000 (10-5 or 0.001 percent) per annum by 2050. This entity is powerful as it has the power to allocate a budget (Rijkswaterstraat, 2021).
Delta commission	The Delta commission is responsible for issuing advice to the government concerning the protection of the Netherlands against the consequences of climate change (DeltaComission (2008)). It is a political actor without any decision-making jurisdiction. However, as an advisor to Rijkswaterstraat, it yields a non-negligible amount of power. It also takes part in flood risk management debates and has voting rights
Gelderland province	The Gelderland province is located upstream of Overijssel, which means the policies it chooses to implement affect the municipalities downstream. Gelderland represents the interests of the Municipalities of Doesburg, Cortenoever, and Zutphen containing dike rings 1, 2, and 3 respectively which are upstream and located at most critical regions. Gelderland is mainly a political actor and has as the main agenda to defend the safety of the municipalities it represents. Moreover, as a member of the VVD party, the Gelderland province must also ensure its most important values of economic freedom are not limited by the selected policy (Kwakkel (2021)).

Zutphen municipality	The Zutphen municipality (located in the Gelderland province) is located in the dike ring 3. It is concerned as it is an urban area and would greatly suffer from a flood. Its main interest is the heightening of dikes which will ensure its citizens do not lose lands. However, if the recommended policies will imply loss of land, the municipality wants its citizens to be compensated(Kwakkel (2021)).
Doesburg and Corteno-ever municipality	This municipality (Located in the Gelderland province) mainly consists of agricultural lands with a high youth population practicing modern agriculture. It is located upstream. A room for the river infrastructure project is possible there if adequate compensation is ensured for the farmers (Kwakkel (2021)).
Overijssel province	The Overijssel province is located downstream which means it is affected by the policies of the Gelderland province. Overijssel wants to ensure the safety of its citizens while minimizing costs. It represents the municipalities of Gorssel and Deventer. The province of Gelderland has no direct contact with these municipalities (Kwakkel (2021)).
Gorssel municipality	This municipality is located between Zutphen and Deventer on the Ijssel river and is part of the Overijssel province. Its objective is to guarantee the safety of its citizens while minimizing water management costs.
Deventer Municipality	The Deventer municipality is the most downstream municipality in the Overijssel province. It is hence the least powerful as it is affected by the policies of all the municipalities located upstream. Its objective is to guarantee the safety of its citizens while minimizing water management costs.
Transport company	The transport company is worried because, if the river is widened, the water might become too shallow. As a result, this would reduce the river's utility as a pathway for the transport of merchandise (Kwakkel (2021)).
Environmental interest groups	Environmental interest groups are worried and exert pressure on the government to avoid the construction of new dikes, which would be detrimental to the environment (Kwakkel (2021)).

Table 1.1: Stakeholder Perceptions, Powers and Interests

1.3. Formulating the problem: The province of Gelderland's perspective

For the province of Gelderland, the safety of its citizens is the determining factor. However, it is also important for the province to defend the economical interests and the economical freedom of its citizens. The province of Gelderland is responsible for dike areas one, two, and three and needs to navigate this complex political arena to ensure the best policy choice for its people. This can only be done by proposing policies that can be accepted by the key players and context setters. Formulating a research question is helpful to identify the knowledge needed to solve complex multi-stakeholder problems. In the case of the province of Gelderland, the question can be formulated as:

"What policy should the province of Gelderland implement to ensure the safety and minimize the social and economic costs of its citizens, while also ensuring critical mass of support from other stakeholders in the political arena?"

In order to answer this main question, the following sub-questions should also be considered:

- Which KPIs matter most for the Gelderland province to evaluate flood protection policies?
- What would be the consequences inflicted on the Gelderland province in the scenario where no flood protection measures are implemented?
- What uncertainties influence the outcomes of interest?
- What combination of flood mitigation measures would guarantee the safety of Gelderland citizens in the event of a worst-case scenario?
- What are the policies protecting Gelderland citizens in a worst-case scenario, which are susceptible to being accepted by the critical mass of stakeholders necessary to implement the project?
- What is the best strategy for the Gelderland province to convince the other stakeholders to implement the policies which guarantee the safety and economic freedom of its citizens?

1.4. Report structure

Flooding of the Ijssel River has the potential to cause casualties and create a considerable amount of physical damage. In order to manage this risk, there are three possible measures that can be taken: dike heightening, early alarm system implementation, and creating room for the river. The objective of this report is to determine what arrangement of these policies is most effective in reducing the casualties and material damages inflicted on Gelderland citizens. These different arrangements can be simulated through an exploratory mathematical model analysis which gives the expected casualties and material damages. Additionally, this model allows for a better understanding of the problem by taking into account financial variables such as room for the river costs, dike investment costs, and evacuation costs. Mechanical variables such as dike failure probability, the growth of breach width, and wave shape are also taken into consideration.

As a result, the structure of the report is as follows: first, the research method and the problem-solving approach are determined, then in a second part, the exploratory model analysis and policy optimization results are presented and analyzed. Following that, a discussion and critical evaluation of the results ensues. Finally, conclusions and recommendations followed by a political reflection are made to allow the province of Gelderland to shape an efficient strategy.

2

Research Methodology

2.1. The Ijssel model

The following section explains the model used to assess and compare the different policies which the province of Gelderland might consider. The different policies are tested and compared in the context of an Exploratory Modeling Analysis (EMA) framework. First, the main principles of EMA are explained, then the EMA strategies used to answer the research questions formulated in Section 1 are laid out and justified. The scope of the model encompasses all regions in the first step to understand the impact of Gelderland province policies on other actors. Then, the scope is narrowed down to Gelderland municipalities for policy optimization.

2.1.1. Exploratory Modeling Analysis and the XLRM method

Exploratory modeling is used to understand the implications of decision-making in the context of systems that are affected by irresolvable uncertainties. This approach consists of conducting a series of computational experiments with the objective of resolving these uncertainties. The XLRM framework, also known as the system diagram, is one of the key ideas underpinning the design of an exploratory modeling workbench (Kwakkel (2017a)). The model (R) is a set of equations determining the relationships between its subcomponents. It is a mathematical representation of the underlying mechanisms intrinsic to the system. The model is used as a function where R(X, L) = M. Indeed, the uncertainties (X) and the policies (P) are variables that can be inputted in the function (R) to obtain the expected outcomes (M).

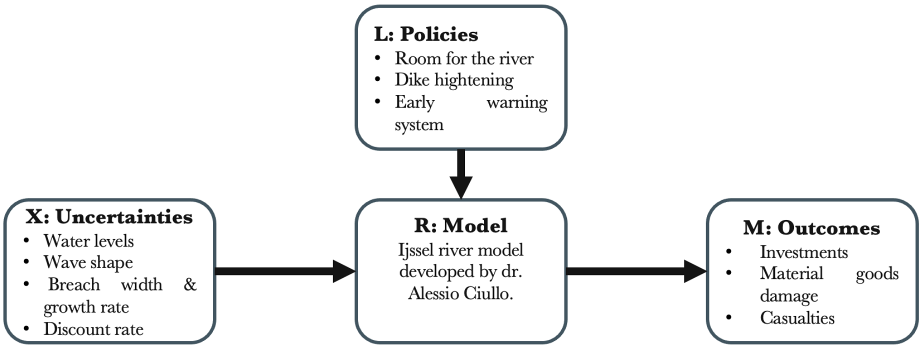


Figure 2.1: The XLRM Framework.

2.1.2. X - Uncertainties

Within the context of an Exploratory Modeling Workbench, insolvable uncertainties are always modeled as exogenous factors (X) (Kwakkel (2017a)). In the case of the Ijssel river, the exogenous factors are water levels which might cause a breach in the dikes (*pfail*), wave shape (*ID flood wave shape*), breach width (*Bmax*), breach growth rate (*Brate*), and finally the discount rate which determines the present value of the future expected damage due to flooding events.

2.1.3. L - Policy Levers

Three main policy levers are identified. The first one is room for the river (*Rfr*), which aims to increase the volumetric flow capacity of the waterways to reduce the risk of flooding. The river widening would reduce the surface area of lands in regions contiguous to the Ijssel. River widening would also reduce the depth of the river, which might limit the river's capacity for fluvial merchandise transport. The second lever is dike heightening (*DikeIncrease*) to reduce the risk of flooding in the area where it is implemented but has the potential to transfer the risk to downstream locations. Finally, early warning systems (*EWS_DaysToThreat*) can be implemented to assist evacuations and reduce the number of casualties in the eventuality of a flood. These flood mitigation infrastructures are funded by Rijkswaterstaat and can be implemented in five different locations. An overview of the different room for the river projects and municipalites can be found in the appendix (A.1).

2.1.4. R - Model

The Ijssel river model was developed by Alessio Ciullo in the context of his Ph.D. research (Ciullo et al. (2019)). The model investigates how the different flood mitigation policies perform in various scenarios and accounts for uncertainties. The water flow in all dike area controls and their interrelations are described with mathematical equations to describe the Ijssel river system behavior. This is particularly useful, as the numerous policies, which can affect both the physical flow of water in the Ijssel river and the behavior of contiguous populations, can be implemented in five distinct areas. Moreover, policies implemented upstream can transfer additional risks downstream which increases the system's complexity. As a result, the model allows one to determine the best policies within a wide array of options by simulating their outcomes. The planning window is two hundred years with 3 planning steps and each planning step being sixty-six years.

2.1.5. M - Outcomes

As it can be seen in Figure 3, outcomes consist of casualties, total material damages, and necessary investment costs specific to the flood management areas of interest. They are used to assess the performance of each policy.

2.1.6. KPI identification and problem translation

Stemming from Section 1, the problem was identified as determining the policies which minimize the costs in terms of casualties and material goods in the Gelderland province while obtaining the critical mass of support necessary for project completion. In order to solve that problem through exploratory modeling analysis, it needs to be translated into mathematical equations. The problem can hence be broken down into two parts:

Problem formulation 1: All municipalities

The first part is concerned with determining the effect of implementing some policies in Gelderland on other regions through a sensitivity analysis. This step is necessary to propose policies that can be accepted by other stakeholders. Thus the selected KPIs for Problem formulation 1 is:

- A.1 Doesburg Total Costs
- A.1 Doesburg Expected Number of Deaths
- A.2 Cortenoever Total Costs
- A.2 Cortenoever Expected Number of Deaths
- A.3 ZutphenTotal Costs
- A.3 Zutphen Expected Number of Deaths
- A.4 Gorssel Total Costs
- A.4 Gorssel Expected Number of Deaths
- A.5 Deventer Total Costs
- A.5 Deventer Expected Number of Deaths
- Room for the river Total costs
- Expected evacuation costs

The Aggregated costs are formulated as :
Aggregated Total Costs = Dike investment + Expected Annual Damage

Problem formulation 2: Policy optimisation for Gelderland
The second problem formulation is concerned with finding the best arrangement of policies to reduce the risk of casualties and material goods as much as possible in Areas one, two, and three, which are within the Gelderland region. Thus the selected KPIs are:

- A.1 Doesburg Total Costs
- A.1 Doesburg Expected Number of Deaths
- A.2 Cortenoever Total Costs
- A.2 Cortenoever Expected Number of Deaths
- A.3 Zutphen Total Costs
- A.3 Zutphen Expected Number of Deaths
- Room for the river Total costs
- Expected evacuation costs

The Disaggregated costs are defined as :
Disaggregated Costs = Separate Dike Investment Costs + Annual Damage

2.2. Exploratory Modelling and Analysis

The problem at hand presents different issues stemming from different fields. In fact, not only physical and natural characteristics changing through time must be analyzed, but also the economic and political discussions resulting from the latter. Thus, it becomes clear that the following is a socio-technical problem. In order to understand the effects that different policies would entail, different simulation methods can be utilized. In this case, Exploratory Modelling Analysis (EMA) using 'ema_workbench' was used. EMA_workbench is an open-source python library developed by J.H. Kwakkel. Among its many utilities, the EMA_workbench allows to compare different policies throughout different scenarios using state of the art optimization techniques and helps understand which ones work best for a determinate situation and how to ameliorate the chosen policies (Kwakkel (2017b)).

Precise steps were delineated to perform the analyses. Firstly, an open exploration was done followed by a directed search. Essentially, the scope and the results obtained were made more and more specific with each step.

2.2.1. Open Exploration

In order to understand how the developed system for the province of Gelderland would behave under different assumptions, an open exploration was carried out to set a base case. Essentially, the system is initially analyzed in a more holistic way, continuously and systematically sampling different uncertainty levels. In this report, the open exploration section was further subdivided between an initial scenario discovery and a successive sensitivity analysis. As each method has its own limitations, two different approaches were followed for cross-verification.

Initial Scenario Discovery

As previously mentioned throughout the report, it is vital to compare different scenarios implementable for the Ijssel River. One technique to do this is the Patient Rule Induction Algorithm (PRIM). The latter has been found to be particularly useful in domains in which there is a need for determinate actions aimed at implementing specific adaptive policies (Hamarat et al. (2013)). Dealing both with categorical and continuous uncertainties, the PRIM algorithm is able to gradually leave out unwanted uncertainty sub-spaces, making the latter smaller and smaller (Hamarat et al. (2013)). In this case, an initial scenario discovery was done to find the uncertainties co-related to the highest number of deaths. This was done to identify uncertainties influencing the expected number of deaths at each location. In addition, dimensional stacking was also performed which helps visualize trends in a high-dimensional space.

Sensitivity Analysis

As stated by Jaxa-Rozen and Kwakkel, sensitivity analysis is a recognized “key step for analyses which involve the assessment and propagation of uncertainty in mathematical models” (Jaxa-Rozen and Kwakkel (2018)). In the following report, two sensitivity (or vulnerability) analyses were made. Namely a first one for the uncertainties present in the model and a second one tackling the levers. Essentially, once the uncertainties having the most influence on the outcomes were found (e.g., number of deaths), the same process was done to find which policy levers most influenced the outcomes. In both cases, SOBOL sampling was used, which although despite being computationally expensive, presents fairly accurate and easily interpretable results that accurately summarise the behavior of the model (Cariboni et al. (2007)). When using SOBOL sampling, the SALib external Python library is preferred (Herman and Usher (2017)). SAlib is used for calculating SOBOL indices resulting from the generated input samples (Jaxa-Rozen and Kwakkel (2018)).

2.2.2. Directed Search

Directed search is used to search over the decision levers in the worst-case scenario in order to find good candidate strategies. The first step in such a process would be first to delineate Pareto-optimal policies by performing Model Optimization. Subsequently, such solutions would have to be further filtered down. This can be done by utilizing Many-Objective Robust Decision Making.

Model Optimization

The aim of the Model Optimization is to find optimal policies for the worst-case scenario. In other words, the policies that would best mitigate such a disastrous scenario. A worst-case flood scenario would be when all the dikes fail, the flood wave shape is on the maximum due to climate change and discount rates are low simulating bad economic implications. Such a process of finding the best policies can be done by utilizing Multi-Objective Evolutionary Algorithms (MOEA) (Eker and Kwakkel (2018)). This will result in a set of Pareto-optimal solutions.

Many-Objective Robust Decision Making

Many-Objective Robust Decision Making (MORDM) is a method used to undertake decisions under deep uncertainty in situations where different objectives are present

(Eker and Kwakkel (2018)). In this case, it is indeed a multi-objective problem as there is a need to assure that no deaths will occur under any circumstances while at the same time maintaining costs under a certain economic boundary. MORDM will first be used to filter out any policies under which deaths may occur. In fact, MORDM uses MOEAs within one reference scenario to compare different policy alternatives (Bartholomew and Kwakkel, 2020). Thereafter, the same process will be used to filter out policies presenting high costs of room for the river. Lastly, two robustness indices are used to analyze the robustness of the shortlisted policies: the Signal to Noise Ratio and the Maximum Regret measure.

2.2.3. Scenario Discovery for potential risks and limitations of proposed policy

A final scenario discovery was carried out to discover uncertainties to resulting unfavorable outcomes despite implementing the selected policy. In addition, since the Province of Gelderland is located upstream, the selected policy was tested under uncertainties also for downstream provinces. Secondly, as written in Section 1.3, one of the goals of this report is to propose policies that will be accepted also by the other stakeholders involved, including other provinces. Hence, in order to promote cooperation between different provinces, it is vital to ensure that the proposed policies will not negatively affect the rest.

3

Results

3.1. Open Exploration

3.1.1. Scenario discovery - No policies

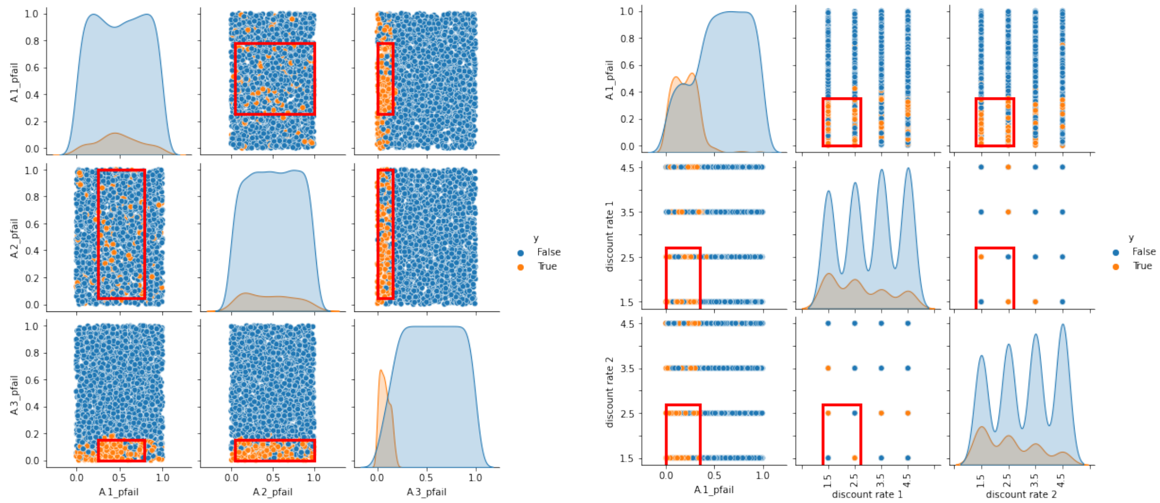
Experimental setup

The first step in the open exploration is to find out how the system behaves when there is no policy implemented starting from an aggregated view by looking at the whole Ijssel river and then zooming in on the different dike rings for a more in-depth analysis. For the aggregated view of the whole Ijssel river, 2000 randomly created scenarios are used with problem formulation ”0”. For the regional analysis, 4000 randomly generated scenarios are created using problem formulation 3.

Results

The results of the aggregated analysis of the whole Ijssel river in the case that there is no policy implemented can be found in Figure B.1. In the base case, the number of deaths can vary between 0 and 6 and the expected annual damage can go up to roughly 6 trillion euros. From these results, it becomes clear that an improvement in flood security is an absolute necessity.

A prim analysis is conducted to find out under which circumstances the 10 % of most casualties are expected in the Ijssel river (see Figure 3.1a). A low A3 pfail clearly results in the most amounts of deaths, meaning that a weak dike ring in Zutphen results in the most casualties. Another interesting outcome is that a strong dike upstream has a negative outcome on the number of casualties. This will be discussed in more detail later. The expected Annual damage is highest in scenarios with a weak dike in area 1 and low discount rates as can be seen from Figure 3.1b.

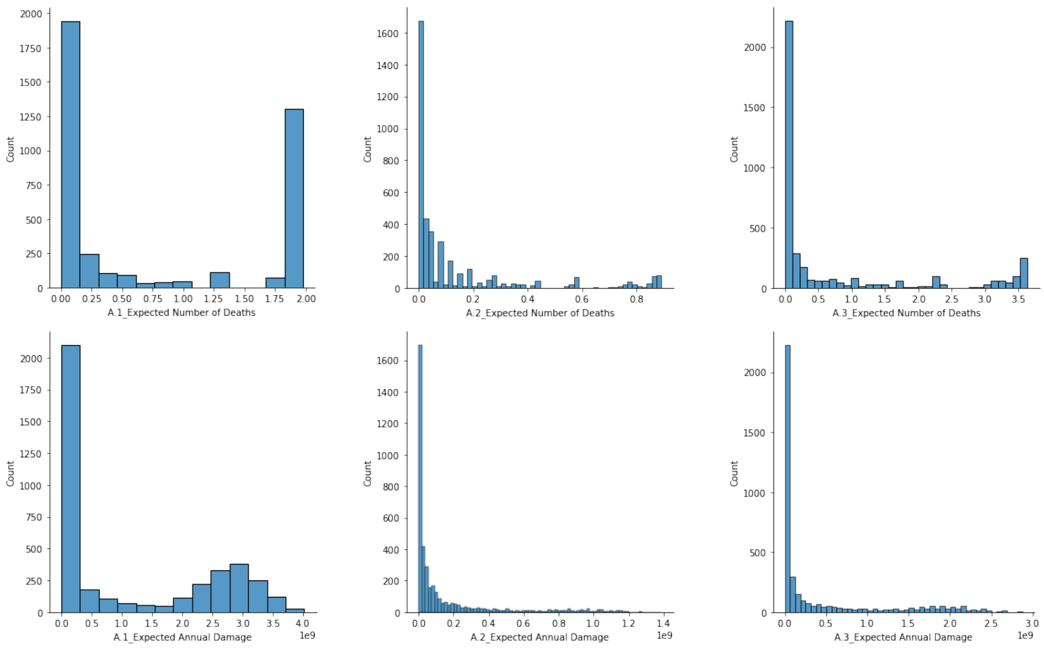


(a) Uncertainties resulting in 10% of most deaths scenarios.

(b) Uncertainties resulting in 20% of most damage scenarios.

Figure 3.1: Prim anaylisis of aggregated results.

By taking a closer look at the different histograms for the expected number of deaths and expected annual damage of the different municipalities (figure 3.2 and figure B.2), the previously made point becomes even clearer. From these histograms it becomes evident that the most damage occurs most often in Doesburg while the most deaths occur in Zutphen. Doesburg is the municipality with the highest frequency of the expected number of deaths.



(a) Doesburg

(b) Cortenoever

(c) Zutphen

Figure 3.2: Histograms of expected number of deaths and expected annual damage in the different municipalities in Gelderland if no policy is implemented.

From the prim and dimensional stacking analysis for each municipality (See Appendix Figure B.3, B.5, B.6), it can be concluded that a low dike strength (pfail) and thus weaker dikes in the specific municipality has the biggest contribution towards deaths and damage in that specific municipality. High dike strength (pfail) values in dikes (strong dikes) more upstream also have a contribution towards a higher chance of flooding and thus more deaths and damage in a specific municipality.

3.1.2. Scenario discovery: Levers analysis

Experimental setup

To analyze which levers have an impact on the number of deaths and the damage in the municipalities, a scenario discovery was done using 4000 randomly generated policies with Latin Hypercube as sampling technique and two predefined scenarios. The first scenario is a reference scenario with average values for the uncertainties while the second scenario has low pfail values (all pfail values are 0.1, see appendix for specific values **??**). The low pfail value scenario was chosen since this has the most negative impact on the preferred outcomes. It has to be mentioned though that drawing conclusion from the differences in these two scenarios has to be taken with great caution because of the complexity of the system. In order to get a deeper understanding of the system, a sensitivity analysis is conducted which can be found in the next section.

Results

On the results of these scenarios, a prim and a dimensional stacking analysis is conducted again to find the scenarios in which there are no deaths in the municipality. The specific figures can be found in Figure 3.3 and in the Appendix (B.1.1). From these results, it becomes clear that dike increase has the biggest impact in reducing the total number of deaths, while certain room for the river projects also has a positive impact on this. Another interesting observation is that a higher dike increase in dike rings more upstream results in a higher amount of deaths in a municipality located more downstream. This effect is highest in the scenario with low pfail values.

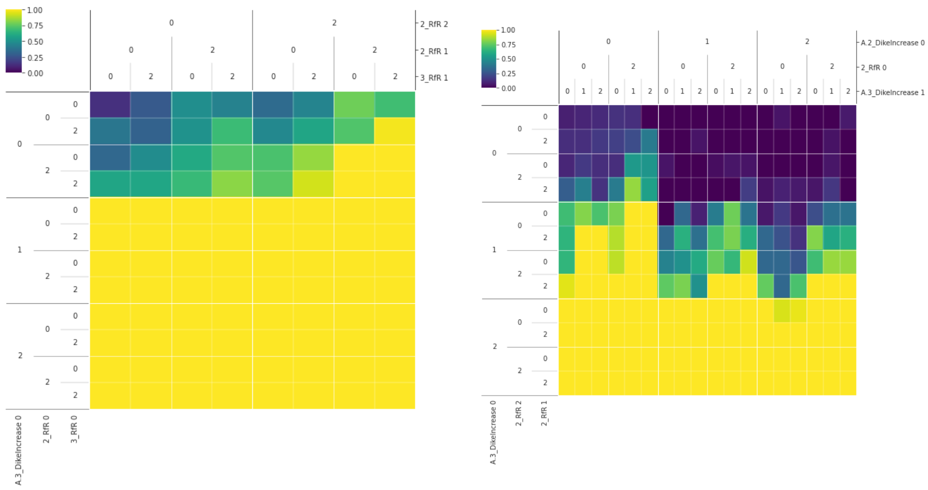


Figure 3.3: Dimensional stacking of the influence of certain levers that result in zero deaths in Zutphen in the reference scenario (left) and the pfail scenario (right).

3.1.3. Sensitivity Analysis

Sensitivity Analysis is done to further identify the key uncertainties and policy levers influencing the outcomes. A holistic approach is taken during this analysis to prioritize overall safety by focusing the analysis on the number of deaths in each area. The results are used for factor prioritization where the most critical factors are determined which when fixed to their true value would lead to a reduction in the output variance. This is especially helpful in the dike model where there are 19 uncertain factors and more than 12 outcome variables. Problem formulation 1 is selected which returns outcomes for all the regions in the model.

Vulnerability Analysis - Uncertainties

Experimental setup

'Sobol' sampling was used for sampling uncertainties. Sobol analysis requires a minimum of N(2k+2) samples where N is a baseline number of experiments required to cover the uncertainties and k is the number of uncertainties Saltelli (2002). Thus, this resulted in 1000 * (38 + 2) = 40,000 experiments in total.

Findings

The results from SOBOL analysis using first-order and third-order derivatives showed that the probability of dikes failing in an area (*A_pfail*) is most influential to the outcomes of expected deaths and total costs of that area. The full analysis is given in Appendix B.2. The results are further visualized in a heatmap as shown in Figure 3.4. The highest influence is from dike failing in Zutphen (*A3_pfail*).

It was interesting to note however, that Gorssel's Total Costs and Expected Deaths are influenced to some extent by Zutphen's and Cortenoever's dikes failing, which could be because Gorssel being a downstream municipality is affected by what happens upstream. Furthermore, expected evacuation costs across all regions are also majorly influenced by Zutphen's dikes failing. This can be seen in Appendix Figure B.10.

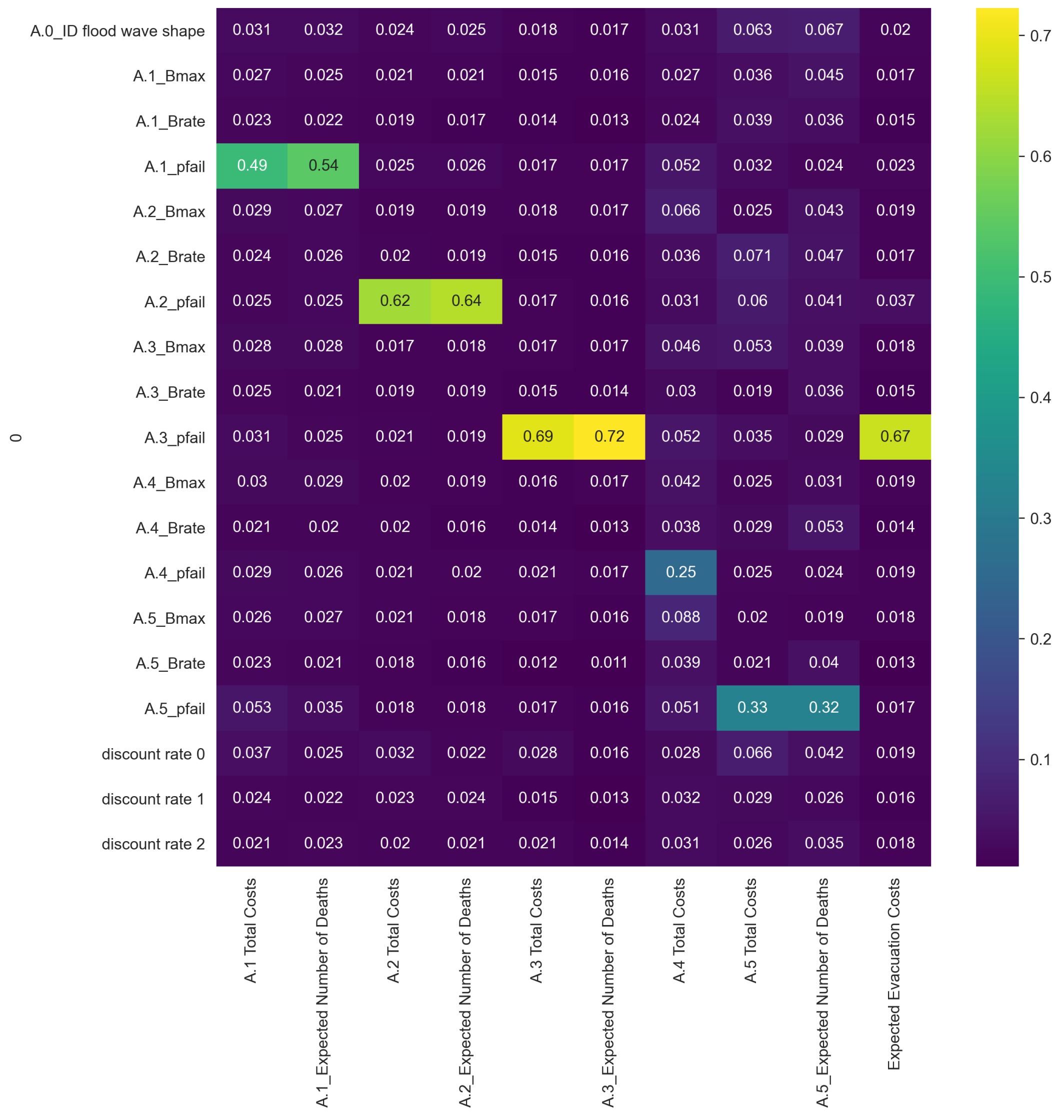


Figure 3.4: Feature Scoring: Influence of uncertainties on the outcomes

Sensitivity Analysis - Levers

After identifying the key uncertainties in the model, another sensitivity analysis was performed to identify the key policy levers for avoiding casualties in all the regions.

Experimental setup

A similar approach as that of vulnerability analysis for uncertainties (section 3.1.3) was followed in the experimental setup.'Sobol' was used for lever sampling. SaLib algorithm was run to perform sensitivity analysis on 31 policy levers under 1000 random scenarios, thus the total number of runs were ($N(2K+2)$) 64000.

Findings

The sensitivity analysis for levers helped in identifying the levers influencing the expected number of deaths. An overview of the results through feature scoring (Figure: 3.5) (reference here) showed that dike heightening is most important for bringing down the expected number of deaths in the respective regions. In addition to this, a deep dive into the Salib index (Figure B.11) helped in identifying that the dike increase has a direct influence on the expected number of deaths, whereas Room for the river is also effective when used in conjunction with other levers. Thus, sensitivity analysis helped us pinpoint the specific 'dike heightening' and 'room for river' levers for curbing the expected number of deaths. This information is critical for the formulation and selection of candidate solutions.

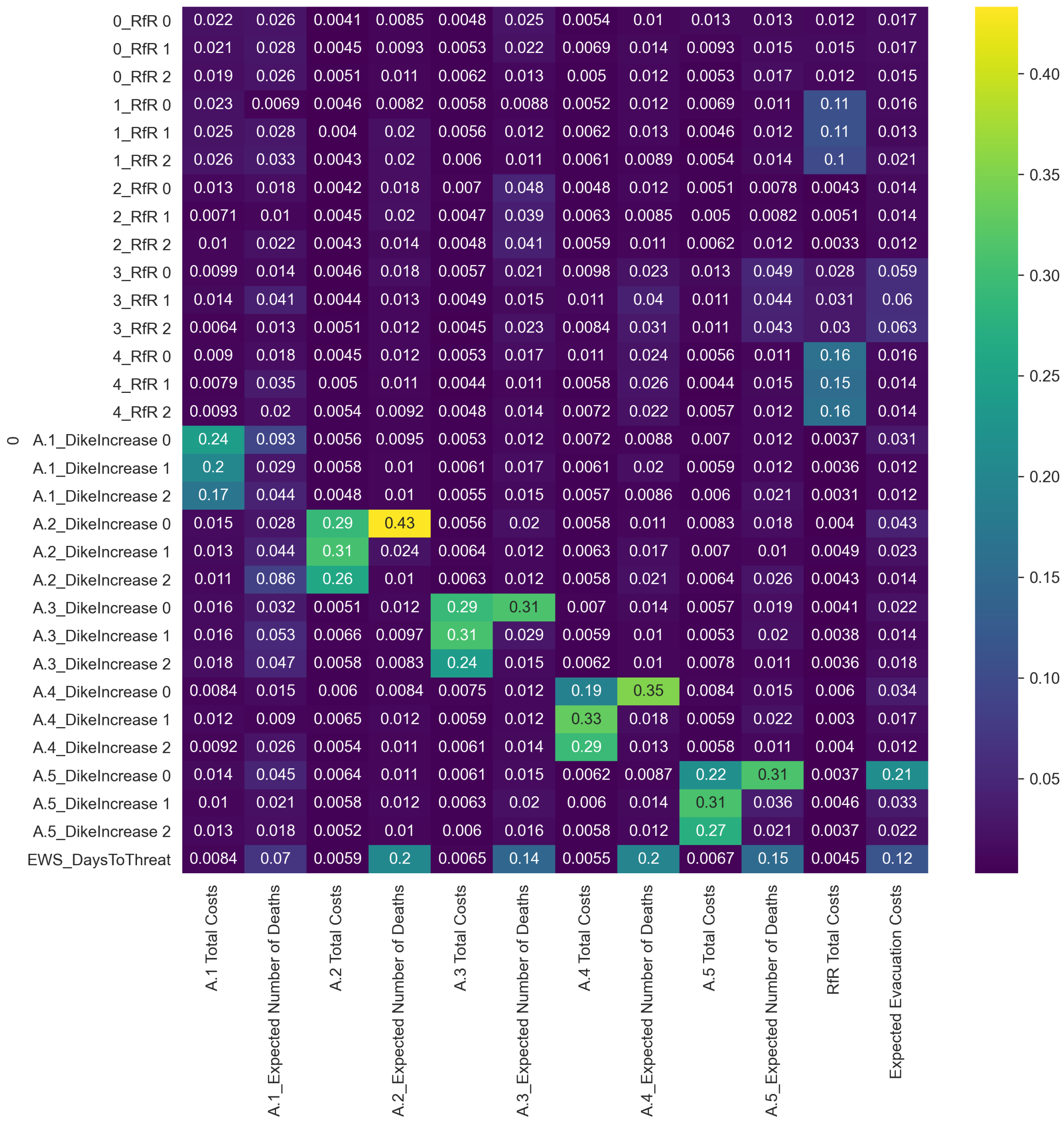


Figure 3.5: Feature Scoring: Influence of policy levers on the outcomes

Limitations

The sensitivity analysis performed has certain limitations which should be taken into account while interpreting the results. The results of sensitivity analysis are derived from the historical data and are dependent on the model assumptions. In addition to this, the graphs generated of the SALIB index exhibit a large number of outliers. This happens when the algorithm fails to converge the indices because of not sufficient samples (Jaxa-Rozen and Kwakkel (2018)). A second run with more samples was not conducted because of time constraints and would be strongly recommended for a stable solution set for further analysis.

3.2. Directed Search using MORDM

After open exploration, a directed search is performed to find a Pareto set of optimized policies for the 'worst case scenario'. For this, problem formulation (2) for Gelderland is used.

3.2.1. Setting Reference Worst-Case Scenario

Experimental Setup

The worst-case scenario of high chances of floods in all the regions is formulated informed by scenario discovery for undesirable outcomes and vulnerability analysis on what factors are most critical. To simulate this, *p_fail* for all the areas are taken as the 20th quantile (lower *p_fail*, higher chances of dike failing), flood wave shape is set to the 90th quantile to represent climate change and discount rates are set to the lowest value of 1.5 signifying higher economic damage in the future. Lastly breach width *Bmax* and breach width model *Brates* are set as 300 and 10 respectively.

Limitations

It is assumed is that if the policy is optimal for a worst-case scenario, it will work for a likely scenario, which may not always be the case. Another main disadvantage of scenario analysis is that incorrect assumptions can lead to skewed results following the principle of "garbage in, garbage out." Scenario analysis is also susceptible to biases of the modeler and tends to be heavily dependent on historical data. To include multi-scenario MORDM, Watson and Kasprzyk (2017) suggest picking scenarios based on the scenario discovery results. However, this is currently outside the scope of this report.

3.2.2. Model Optimization using MOEA - Search Over Levers

Experimental setup

In this step, Pareto optimal candidate strategies are identified on the reference scenario using Multi-Objective Evolutionary Algorithm (MOEA). After setting the worst-case scenario as a reference, optimization was done to search for levers. For optimization, the ema_workbench uses a library called platypus-opt. Epsilon is maintained as 0.1 to balance between granularity and run-time considerations. The number of functions for evaluation (Nfe) is taken as 5000.

Results

After optimizing, 1045 candidate policy solutions were found. Trade-offs for these solutions were plotted and can be found in Appendix C.1. The results showed there were considerable deaths in the three municipalities which is unacceptable to Gelderland. Therefore, to meet Gelderland's goal of the safety of citizens as an utmost priority, the policies are filtered to those having 0 deaths for the three municipalities - Doesberg, Cortenover, and Zutphen. This resulted in 30 policies, the trade-offs for which are visualized in Figure 3.6.

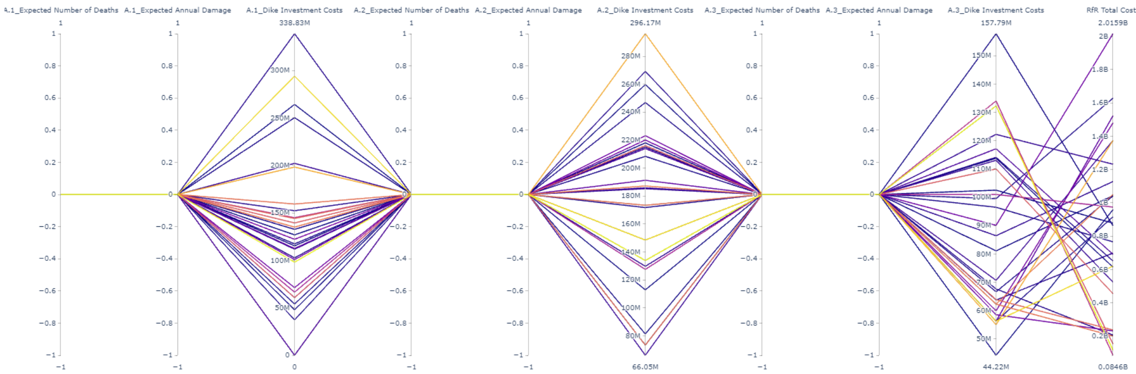


Figure 3.6: Parallel Coordinate Plot: 31 Optimized policies with 0 deaths in Doesberg, Cortenover and Zutphen

Once deaths are limited to zero, there is a wide difference in dike investment costs and total room for river costs. Another mandate for Gelderland is prosperity from free enterprise and economic freedom, which comes from limiting Room for River as they infringe on farmlands. To reflect this, the policies were further restricted to those with minimized total costs of creating room for the river. **This resulted in 3 optimized policies.**

Limitations
Due to technical limitations, convergence for the solutions could not be determined, so it is not known if 5000 function evaluations are sufficient for the goal. More research is needed to find the correct 'epsilon' and number of functions for evaluation (nfe) values for establishing the accuracy of optimization.

3.2.3. Testing optimized policies under uncertainties
In this step, the 3 optimized policies were re-evaluated over the deeply uncertain factors to assess their robustness against these uncertainties. Experiments were run with 1000 random scenarios for each of the 3 policies. Based on the results, robustness analysis is done in the next step.

3.2.4. Identifying robust policies
From the multiple metrics to quantify robustness, each prioritizing a different perspective, two are selected to analyze how robust a policy is in terms of each outcome indicator - **Signal to Noise Ratio**, which is calculated as the mean of a data set divided by its standard deviation and **Maximum Regret** which is defined as the difference between the performance of the policy in a specific scenario and the performance of a no-regret (i.e. best possible result in that scenario).

Signal to Noise Ratio The Signal-to-Noise ratio for the outcomes for each policy is shown in Figure 3.7. The ideal solution would be a low Signal to Noise score for all the outcomes, but such a solution does not exist. There are also downsides to this metric - it does not provide insight into trade-offs between improving the mean and reducing the standard deviation, functions combining mean and variance are not always monotonically increasing, and both good and bad deviations from the mean are treated equally (Kwakkel et al., 2016). So to investigate this further, we use another robustness metric.

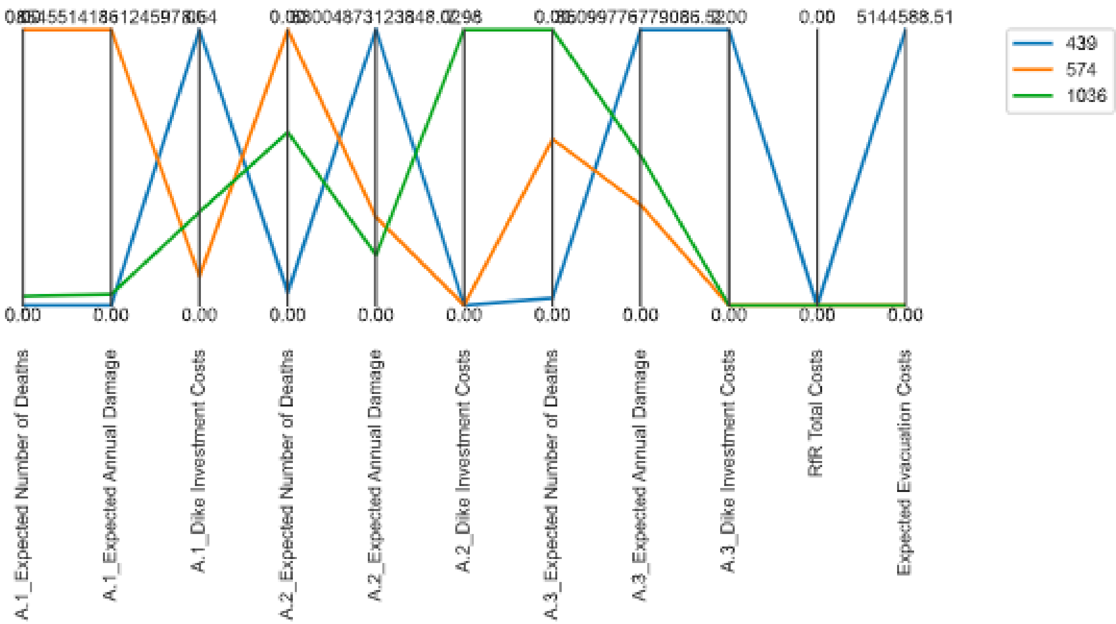


Figure 3.7: Signal to Noise Ratio: Policy 439 (Blue), Policy 574 (Orange) and Policy 1036 (Green)

A robust policy alternative is one that minimizes the maximum regret across scenarios. From Figure 3.8, it is Policy 574 that seems to minimize the max regret the most especially on the expected casualties. Going with this, the selected policy would be **Policy 574** which is talked about in detail in the next section.

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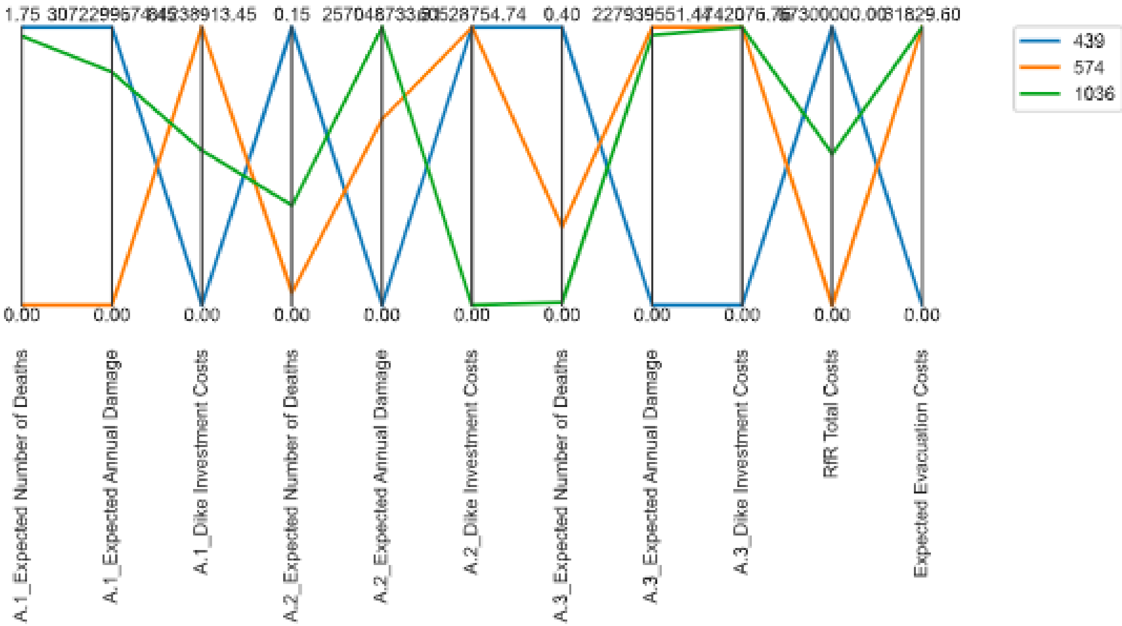

Figure 3.8: Maximum Regret: Policy 439 (Blue), Policy 574 (Orange) and Policy 1036 (Green)

3.2.5. Proposed Policy

The problem of flood management is a complex problem calling for decision-making under deep uncertainties. Thus, there is no magic policy nor one size fits all solution to tackle it. Hence, a combination of policy measures at different locations and planning cycles are recommended to be implemented while being mindful of the possible repercussions discussed in the next section. A detailed reflection on real-life implementation and challenges associated are discussed in section (4)

Planning cycle 1:
A combination of room for river and dike heightening measures is proposed for the first planning cycle. Lowering or removing obstacles from the floodplains and digging bypasses (Kind et al. (2018)) is recommended in Tichelbeekse waard and Welsummer buitenwaarden. Along with this, dike heightening by 6 decimeters in Doesburg, 7 decimeters in Cortenoever, 7 decimeters in Zutphen, 6 decimeters in Gorssel, and 3 decimeters in Deventer.

Planning cycle 2:
In the second planning cycle, dike heightening at Zutphen, Gorssel, and Deventer is proposed by 7 decimeters, 6 decimeters, and 1 decimeter respectively.

Planning cycle 3:
Lastly in the third phase of the planning cycle, the last round of dike heightening is proposed at Zutphen, Gorssel, and Deventer by 7 decimeters, 7 decimeters, and 4 decimeters respectively.

3.2.6. Exploring limitations of the proposed policy

In this section, a scenario discovery is performed to find the scenarios which can influence the KPIs adversely despite the implementation of proposed policy measures. For this purpose, two scenario discovery exercises were performed using PRIM - (1) Discovering adverse scenarios for Gelderland and (2) Discovering adverse scenarios for all municipalities.

Experimental setup
PRIM was used with 1000 random scenarios with the policy set as our selected policy and threshold as 0.5. For the first experiment, problem formulation for Gelderland province was used. From the robustness analysis, it was found our policy results in quite high annual damage in Cortenover. So, the undesirable outcome was set where 'expected annual damage in Cortenover is greater than 0.2.

For the second experiment, after a preliminary analysis of outcomes in Overijssel, an undesirable outcome was set where expected deaths in Deventer were greater than 0.05 (Figure B.11b). A scenario that had more than 0.8 density was selected from the solution space.

Results
Results from the first experiment showed a scenario where the probability of dikes unable to take the hydraulic load in Doesburg is between [0.088464 - 0.999474] and in Cortenover is between [0.000649 - 0.072211] and the flood wave shape is between [6.5 - 132] (figure C.4). These are quite a wide range of values, thus we tried combining the results of this analysis with subsequent analysis. Results from the second experiment showed a scenario where the probability of dikes unable to take the hydraulic load in Doesburg is between [0.045613 - 0.999638] and in Deventer is between [0.000012 - 0.090174] and the flood wave shape is between [0.045613 - 0.999638] (figure C.6). These results in combination with previous results provide information that implementing the proposed policy is not enough and further research is required to prepare a mitigation strategy and avoid unfavorable circumstances.

Limitations
Apart from the inherent limitations of scenario discovery, these results only speak for two boundary conditions. A similar investigation can be conducted for multiple expected outcomes for Overijssel province to explore the associated risks in detail. Because of the constraint of time and scope of this study, a deep dive into the subject is not possible and is strongly recommended for further research.

4 Discussion

Like any model, the Ijssel River model is also not perfect as it does not accurately and completely describe the physical phenomena of water fluidity along the Ijssel River. For example, the porosity of river beds and the topography of the land is not taken into consideration in calculations. This a strategic choice because such a large computerized fluid dynamics model would be complex and computationally expensive. As a result, these necessary simplifications reduce the potential use of the model to strictly exploratory analysis.

When it comes to room for the river policies, the model is not extensive. The costs for relocating citizens are not taken into consideration. Additionally, the model does not include river deepening as an option. Furthermore, the choice for implementing room for the river is binary; there is no flexibility for this policy. As a result, in the case of room for the river policies, the model does not offer an accurate representation of reality.

Nonetheless, the EMA allowed delineating which policies guarantee the safety of the citizens in Gelderland while minimizing material damages. The conclusion of the analysis was that neither dike heightening nor room for the river is optimal as stand-alone policies. Room for the river should be built in Tichelbeekse waard and Welsummer buitenwaarden, to alleviate pressure in more populated areas and dikes should be heightened in Doesburg, Cortenoever, Zutphen, Gorssel and Deventer. This robust policy accounts for three planning cycles which mainly consists of dike heightening over a period spanning decades. It is important to note that heightening dikes can have a ”lock-in” effect because citizens build homes and business activities close to the dikes. As a result, this limits the options of flood mitigation policies. Hence, it is advised for authorities to consider limiting the use of flood plains. Unfortunately, this would be against opportunity costs (Jarl M. Kind and Botzen (2017)). Avoiding ”lock-in” effects is however essential to ensure the flexibility of the policy.

The province of Gelderland is in a powerful position, as its policies affect the province of Overijssel. As a result, if it has the support of its municipalities, it can efficiently navigate the political arena to attain its objective. The main challenge for the Gelderland province is to ensure adequate compensation for citizens living in lands that will be used to make room for the river. This can be done by stating to both

Rijkswaterstraat and Overijssel that a room for the river project is beneficial to Overijssel, while a traditional policy limited to dike heightening would transfer risks downstream. As a result, the most responsible and societally beneficial outcome for both the Gelderland and Overijssel is the scenario where room for the river is created and the displaced citizens are compensated accordingly. This scenario would ensure the safety of citizens while preserving their right to economic freedom.

The room for the river infrastructure is more ecologically friendly but would however affect the fluvial traffic of merchandise downstream due to reduction in water level. As a result, the province of Gelderland would satisfy the requirements of the environmental interest group but not the transport company. The Transport company, albeit not powerful, can exert some pressure in the political arena to reach the outcomes not favored by the province of Gelderland. So, the Gelderland province will have to use its communication skills to persuade other actors in the decision arena about the necessity to implement to policy in the whole region.

5

Conclusion

Located on the Ijssel river, the province of Gelderland is vulnerable to inundations which can cause casualties and economic damages. The province of Gelderland's main duty is to ensure the safety of its citizens and preserve their economic freedom. Finding the best-suited policy was challenging, as, due to the nature of the problem, the possible options for flood mitigation are numerous. Moreover, the political arena involves many stakeholders with different amounts of interest and power and diverging objectives, which further complicates the situation.

The goal of this report was to answer the research question to solve this complex multi-stakeholder problem and determine what arrangement of policies is most effective in reducing the casualties and material damages inflicted on Gelderland citizens: ***What policy should the province of Gelderland implement to ensure the safety and minimize the social and economic costs of its citizens, while also ensuring critical mass of support from other stakeholders in the political arena?***

This question is answered using exploratory modelling approach which yielded a policy that satisfies the conditions imposed on the province of Gelderland (section 3). This policy involves room for the river at two locations along with dike heightening in five distinct areas over three planning cycles of sixty-six years (section 3.2.5). The main challenge remaining for the province of Gelderland is to push this policy forward and ensure its implementation. This topic is extensively discussed in the political reflection (Chapter 6).

6

Political Reflection

In order to make this analysis useful, it is important to show the client; the Gelderland province how the developed policy can be used primarily to resolve the most crucial problems of the municipalities he represents and also how he can convince other actors in the decision arena to vote for this policy. For this, it is necessary to consider the existing challenges and tensions that the proposed policy must address in order to be successful. Table 1.1 about the Stakeholder Perceptions, Powers and Interests can be used to have an insight about what can be the possible challenges. The paragraphs below discuss these in more detail under three major topics:

1. Challenges between the Analyst and the Gelderland Province and Mitigation Strategies
2. Challenges between Gelderland and the Municipalities it represents and Mitigation Strategies
3. Tensions between Gelderland and other actors in the decision arena and Mitigation Strategies

In each case, after describing the challenges, steps taken into account to mitigate these tensions in the analysis are discussed together with the recommended strategies for the decision making process. At the end, risks and limitations of the proposed strategies are outlined.

First, let's recall the recommended policy: In simple terms, the recommended policy involves a heightening of the dikes at Doesburg and Cortenoever as required by the client. However, at Zutphen, a policy involving both heightening of the dikes and providing room for the river at Tichelbeekse waard is advised. Regarding the region of Overijssel, the model recommends as optimum strategy the partial heightening of dikes and the widening of the river at Welsummer buitenwaarden in Gorssel, while suggesting dike heightening at Deventer.

6.1. Challenges between the Analyst, the Gelderland Province and Mitigation strategies

6.1.1. Minding the Assumptions:

According to (Saltelli et al. (2020)), in order to ensure that a model serves the society properly, it is the responsibility of the modeler to mind the assumptions made on the model; so, within the frame of this analysis, no concrete figures were provided in the problem description to delineate the boundary conditions for the model's most important outcomes in terms of expected number of deaths, annual damages or expected annual costs although required by the analyst. This lack of data posed lots of challenges during the modelling phase as Gelderland needed results, but could not provide concrete boundary conditions.

In order to resolve this issue, an open exploration was made using scenario discovery as described by (Kwakkel (2017b)) and a sensitivity analysis was performed to determine which uncertainties and policy levers had the greatest impact (positive or negative) in terms of expected number of deaths, annual damages and total costs in the regions of interest(the worst case scenario). From this, the policies producing the best possible outcomes in terms of safety (least number of deaths, annual damages) and least costs as specified by Gelderland were identified and their conditions determined as most suitable conditions.

In order to mitigate this in the decision making process, a good strategy involving proper communication as proposed by (Kwakkel (2021)) and (Saltelli et al. (2020)) shall be needed . Moreover, since the aim of the decision making is to convince other stakeholders about the suitability of the policy and get funding, the policy maker should have a proper communication of how the boundary conditions determined for this model align with the National Delta Plan 2021's flood reduction objectives.

6.1.2. Consequences of Policy

The consequences of the recommended policy may constitute an important challenge (Saltelli et al. (2020)); due to the excessive desire for model results within the given time frame by Gelderland and complexity of the situation, the analyst could be forced into making an analysis to produce results which look accurate on paper, but in real sense might be wrong and could produce disastrous effects if implemented.

To prevent a false estimation of the consequences of the policy, a directed search was conducted where the aim was to search for results that produce the most suitable outcomes for the worst case scenarios found from the open exploration. Later, the proposed policies were further analyzed on desired outcomes and robustness to find an 'optimal' policy which was then recommended.

Regarding the mitigation strategy, since the Rijkswaterstaat and Overijssel are directly involved in the decision making process, it could be interesting to collaborate with their analysts to verify that the policy is robust and suitable for all regions.

6.1.3. Credibility

The credibility of the whole analysis could constitute a huge challenge in case it is not accepted by the Gelderland province. According to (Yilmaz et al. (2015)), for any modeling and simulation research to be credible, it should be reproducible using the same code, data and software used for the modeling.

To ensure the credibility of the analysis, all the assumptions and experimental setup used is annotated in the code and documented in the report (reference to result section). Also, limitations of every analysis and its impact on the results is discussed in detail. Lastly, results of all the experiments are stored and are attached along with this report for comparison and further reproducibility of analysis.

At the decision making process level, making the data available to other provinces and analysts could ease understanding and acceptance. Moreover,a good communication of the modeling process that lead to the production of these results could serve as a good mitigation strategy.

6.1.4. Decision making under deep uncertainty

Decision making under deep uncertainty and acknowledging the unknowns of the model could constitute a big challenge. Here, the results of the analysis may be completely disregarded by the Gelderland province due to the unpredictability of factors such as climate change which may prove the results of the analysis to be inaccurate. In addition to this,the model used for aiding the decision making process takes only limited uncertainties into the account because of scope and other modelling constraints. This makes the decision arena prone to black swan events which can not be predicted (Makridakis and Taleb (2009)).

As specified by (Eker and Kwakkel (2018)), and also in the course lecture by (Kwakkel (2021)), a combination of a constructive style of decision making and a Many Objective Robust Decision Making were used, whereby the co–construction of the problem and solutions were made at the same time considering the views of all different actors and the client based on the debate information. So, the recommended policy already encapsulates the views and interests of other actors.

In order to ease decision making, a proper communication of the modeling process and results to the different stakeholders will however be required. Here, special emphasis should be made on the fact that the views of the different stakeholders were taken into account based on the debate information. If necessary, the policy maker should make use of the analyst for proper communication.

6.2. Challenges Existing between Gelderland, the Municipalities it represents and Recommended Strategies

The proposed policy will totally satisfy Doesburg and Cortenoever as they will not lose farmlands and will become safe with the heightening of the dikes. However at Zutphen, a tension might arise. This is because the Municipality of Zutphen does not want to lose lands unless they are compensated. So the viability of the policy will depend on whether the total compensation costs will be covered or not. Likewise, due to the fact that the main party in Gelderland is the VVD, they may have challenges promoting a policy which involves providing more room for the river at Zutphen, since it will reduce lands and potentially restrict their economic freedom.

In order to mitigate these issues, an analysis was made for all the municipalities at the Ijssel River to convince Gelderland why the recommended policy is actually the best for them as it will also satisfy all other actors.

Similarly, proper communication of the proposed strategy to all actors present in the decision arena and advocating for the compensation of the citizens of Zutphen in case of land losses due to river widening should be made to avoid conflicts. Moreover, it is important to also convince the municipality of Zutphen about the advantages of creating more room for the river and to closely collaborate with the responsible institutions for the new purposes of the land(which could be to build recreational parks or other facilities as required by the environmentalists)

6.3. Tensions between Gelderland, other actors and Recommended Strategies

Firstly, Overijssel prefers a policy involving the creation of more room for the river in Gelderland. So dike heightening is not a solution they would like at Doesburg, Cortenoever and Zutphen. Regarding the environmentalists, dike heightening is not an environmentally friendly option and they may disapprove this policy. Similarly, the transport company may not be happy with the river widening at Zutphen, Deventer or Gorssel as their water levels will decrease. Finally, the role of the Rijkswaterstaat is to produce a national policy that resolves all conflicts in the region. So, in an event to satisfy all actors, the proposed policy may be disregarded in the national debate in favour of measures satisfying all actors, resulting to increased tensions.

As a model strategy used to mitigate this, the policy was made considering the interests of all actors present in the decision arena as suggested by (Kwakkel (2021)) to ensure an optimum balance between their requirements.

Proper communication with other stakeholders possibly with the use of the model analysts could be a good option to resolve all possible conflicts. Moreover, collaboration of analysts of all regions can be requested to produce a common model or improve the model at hand. Alternatively, Actors and Strategy Modeling strategies like cooperative game theories can be employed to find the optimum resource allocation and pareto optimum for the problem at hand.

6.4. Potential Risks and limitations of the proposed strategy

The proposed strategy is made for Gelderland whose main interest is only about representing its municipalities. Moreover, in the debate, those municipalities only want to hear how their interests are being defended based on the points agreed with Gelderland. However, since the final decision is made after a voting process by all actors, it could be difficult to predict whether this policy will be the preferred one or not, since different actors will present different policies based on their interests and perceptions. In order to mitigate this, the strategy proposed in this report was made to involve the interests of all five municipalities along the river as discussed in the debate(Kwakkel (2021)). This is not necessarily what the actors involved in the debate would like to hear; especially at Zutphen who would not like to lose lands but will ultimately have to concede some lands under the proposed strategy. The same case is observed with Overijssel who prefers river widening, but will be recommended to heighten its dikes for an optimum result for all actors in the arena. It will thus, be the responsibility of the policy maker of Gelderland to use good communication skills and convincing ability to persuade other actors to implement this policy and provide reasonable compensation as a fair trade-off for land losses.

Another possible risk is that Gelderland does not validate the model due Results because the real world is full of complexities, interests, and variating perceptiona and thus, the policy maker may decide not to proceed in a technocratic way.Moreover, Any variation in the policy implementation due to political or bureaucratic reasons may change expected outcomes.Lastly, the potential risks associated with proposed policy are analyzed in controlled situation with limited uncertainties and are prone to black swan events.

Another limitation of the proposed strategy is that it may cause conflicts with Overijssel who prefers river widening in all municipalities along the river. However, from the strategy, dike heightening is suggested as the most suitable strategy at all municipalities with little provision of room for the river (Kwakkel (2021)). The major risk will be denial to implement this policy during the debate.

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A

Appendix A: Problem Formulation

This appendix is intended to familiarize the reader with the problem space. More details on the problem formulation, stakeholders and stakes are discussed in the Chapter 1.3. Following figure A.1 showcases the different dikes and room for river projects along with its nomenclature.

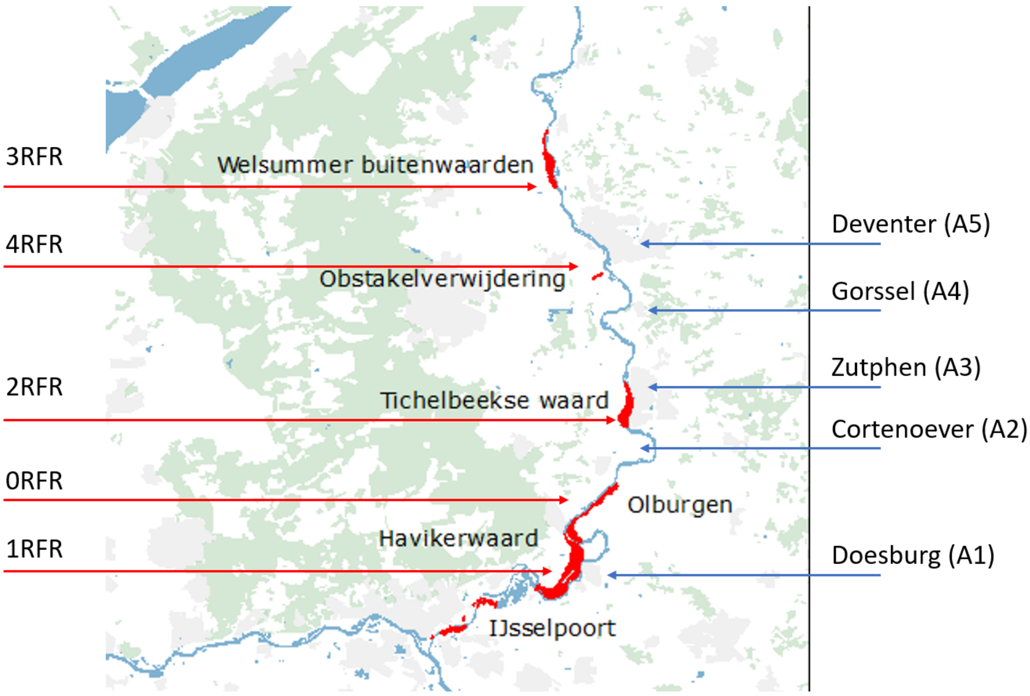


Figure A.1: Overview of different municipalities and RFR projects.

B

Appendix B: Open Exploration

B.1. Scenario discovery - No policies

In this appendix the results from the Scenario discovery of the base case scenario where no policy is implemented are presented.

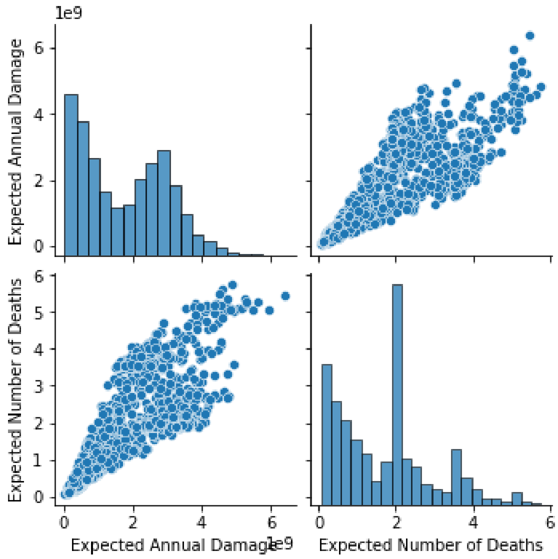
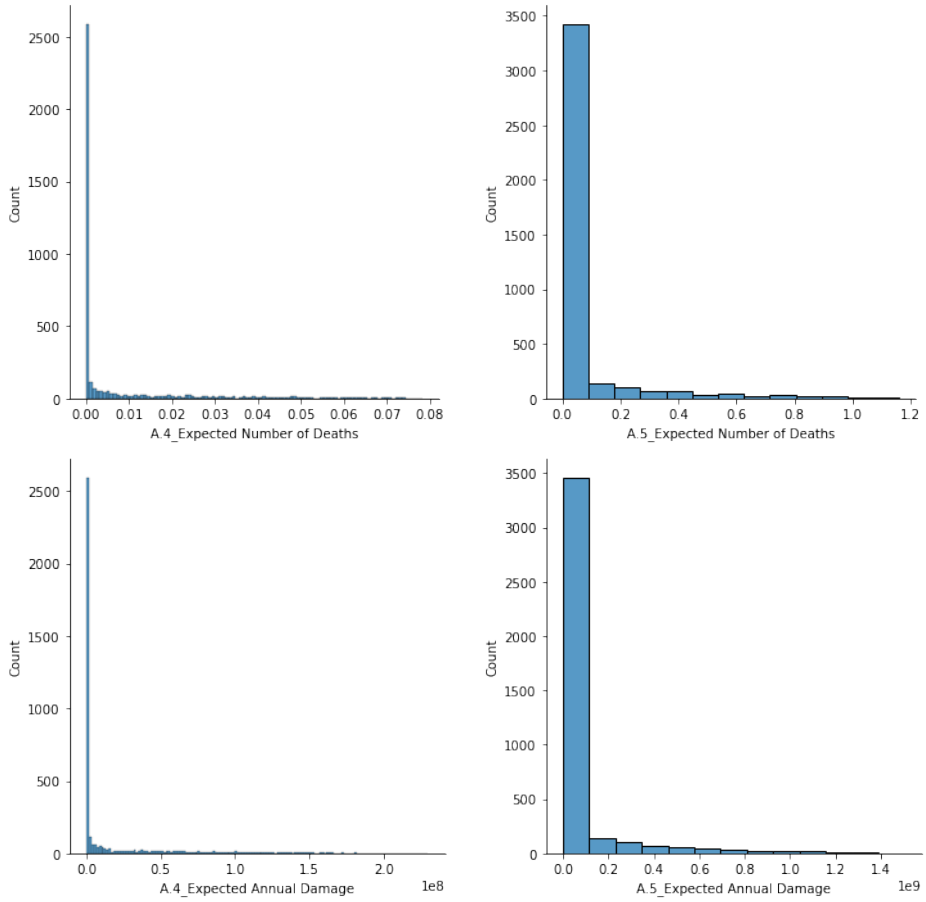
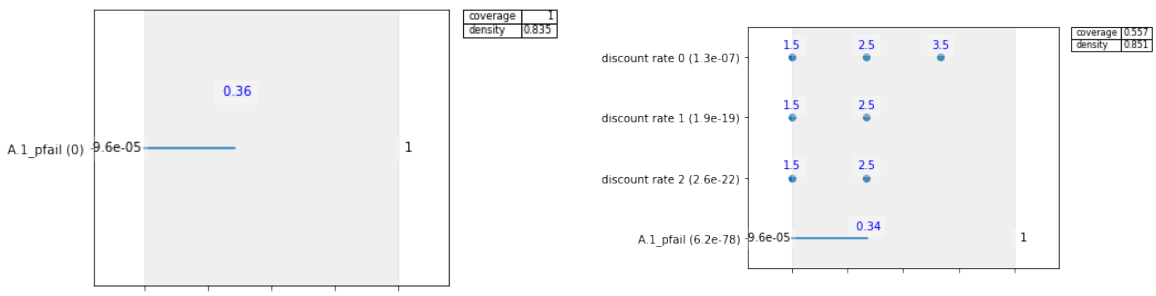


Figure B.1: Expected Annual Damage and Deaths if no policy is implemented.



(a) Gorssel (b) Deventer

Figure B.2: Expected number of deaths and damage in Gorssel (A4) and Deventer (A5) if there is no policy implemented.



(a) (b)

Figure B.3: Prim analysis in Area 1 (Doesburg) for most deaths (a) and most damage (b).

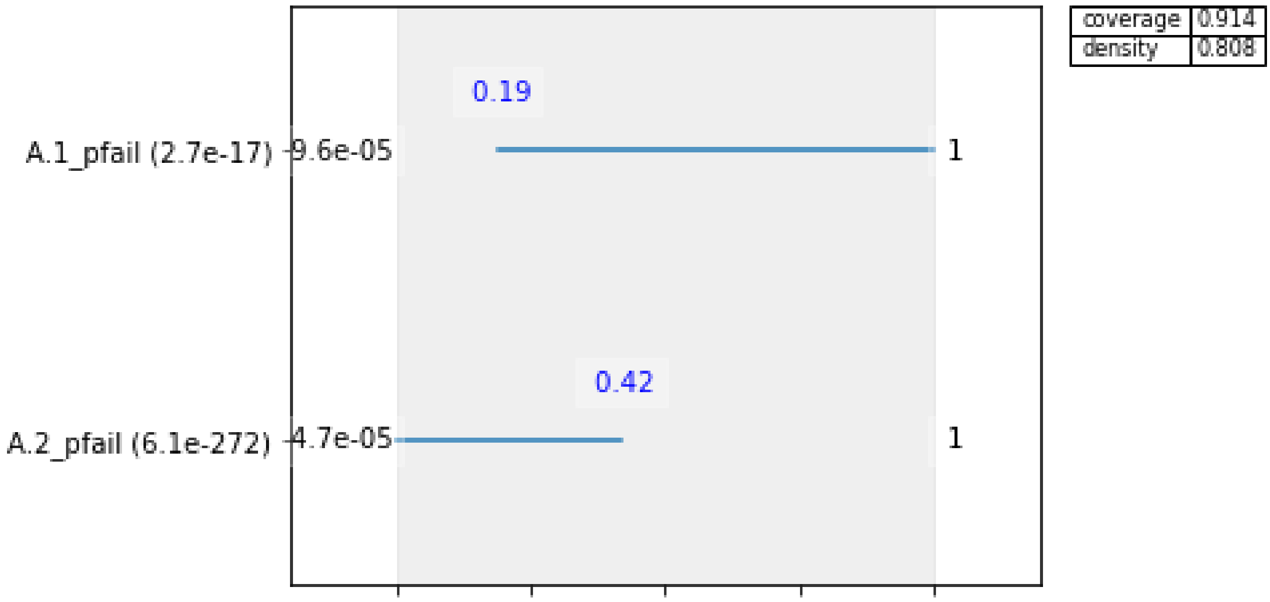


Figure B.5: Prim analysis of deaths in A2

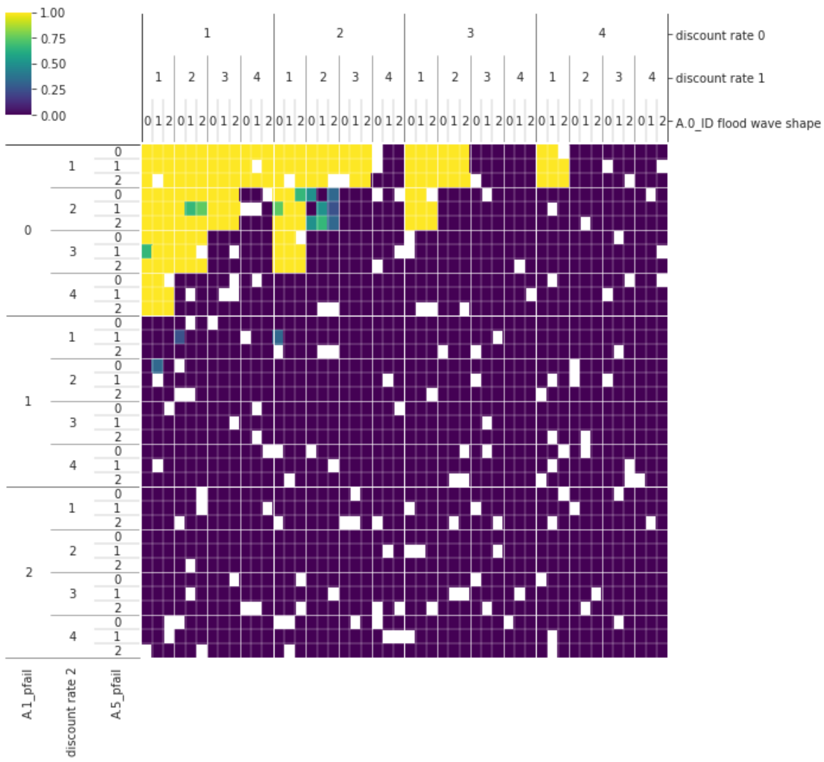
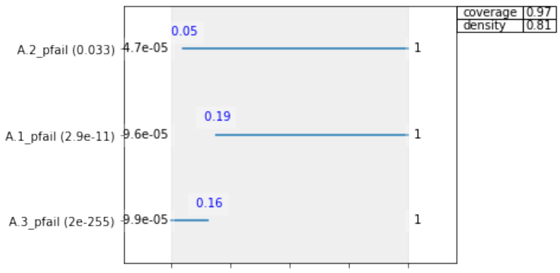
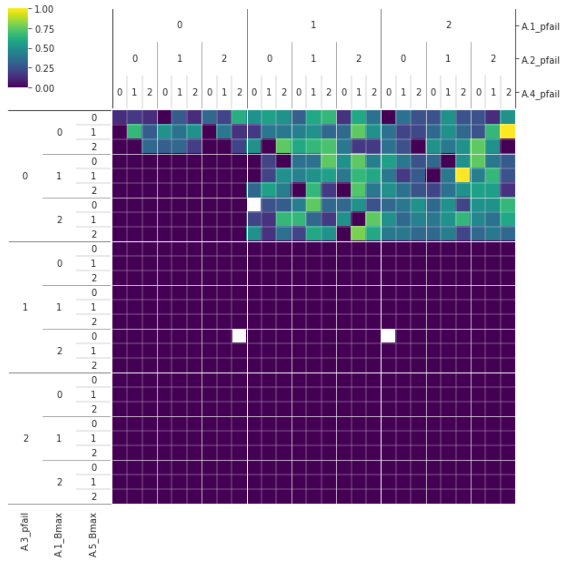


Figure B.4: A1, cases with 10% most damage.



(a)



(b)

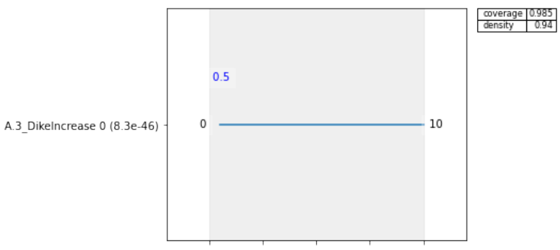
Figure B.6: Prim analysis and dimensional stacking in Area 3 (Zutphen) for most deaths.

B.1.1. Scenario discovery: Levers analysis

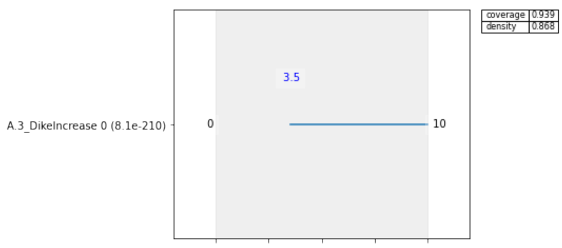
In this section the results of the lever analysis on the pre-defined scenarios are presented. The values for the input values on these scenarios can be found in **??**, the different figures are presented afterwards.

Table B.1: Input values for the lever analysis in the scenario discovery section.

Scenario	Bmax	Brate	pfail	flood wave ID	planning steps	discount rates
Reference	175	1.5	0.5	4	2	3.5
Pfail	175	1.5	0.1	4	2	3.5

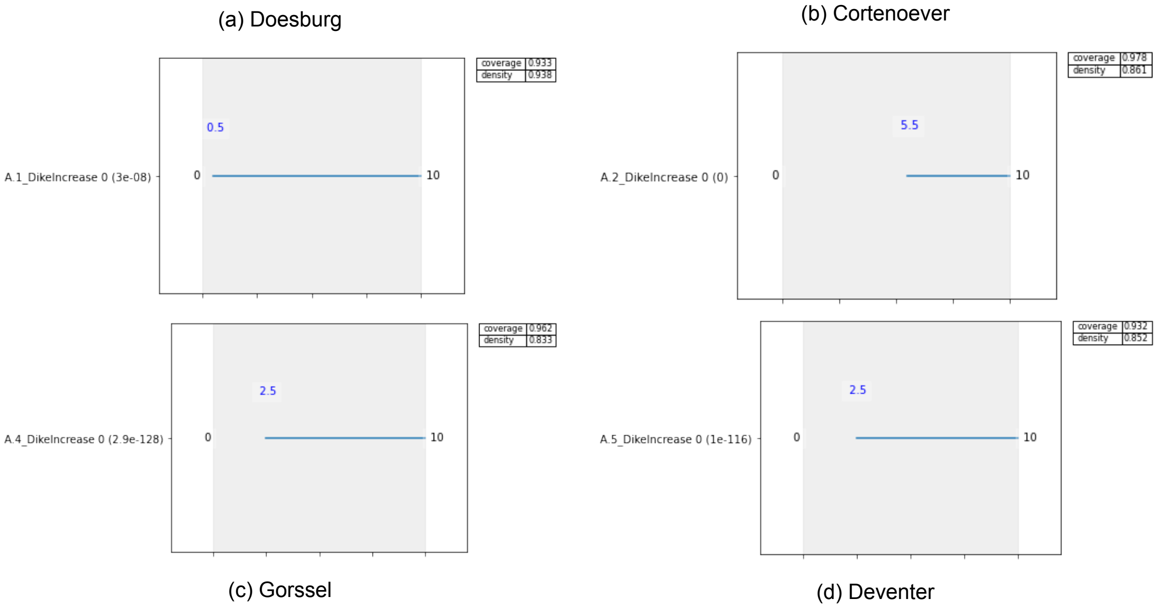


(a) reference



(b) pfail

Figure B.7: Prim analysis in Area 3 (Zutphen) for policies which result in zero number of deaths in the reference scenario and the pfail scenario.



(a) Doesburg (b) Cortenoever (c) Gorssel (d) Deventer

Figure B.8: Dimensional stacking of policies in the different municipalities in the pfail scenario.

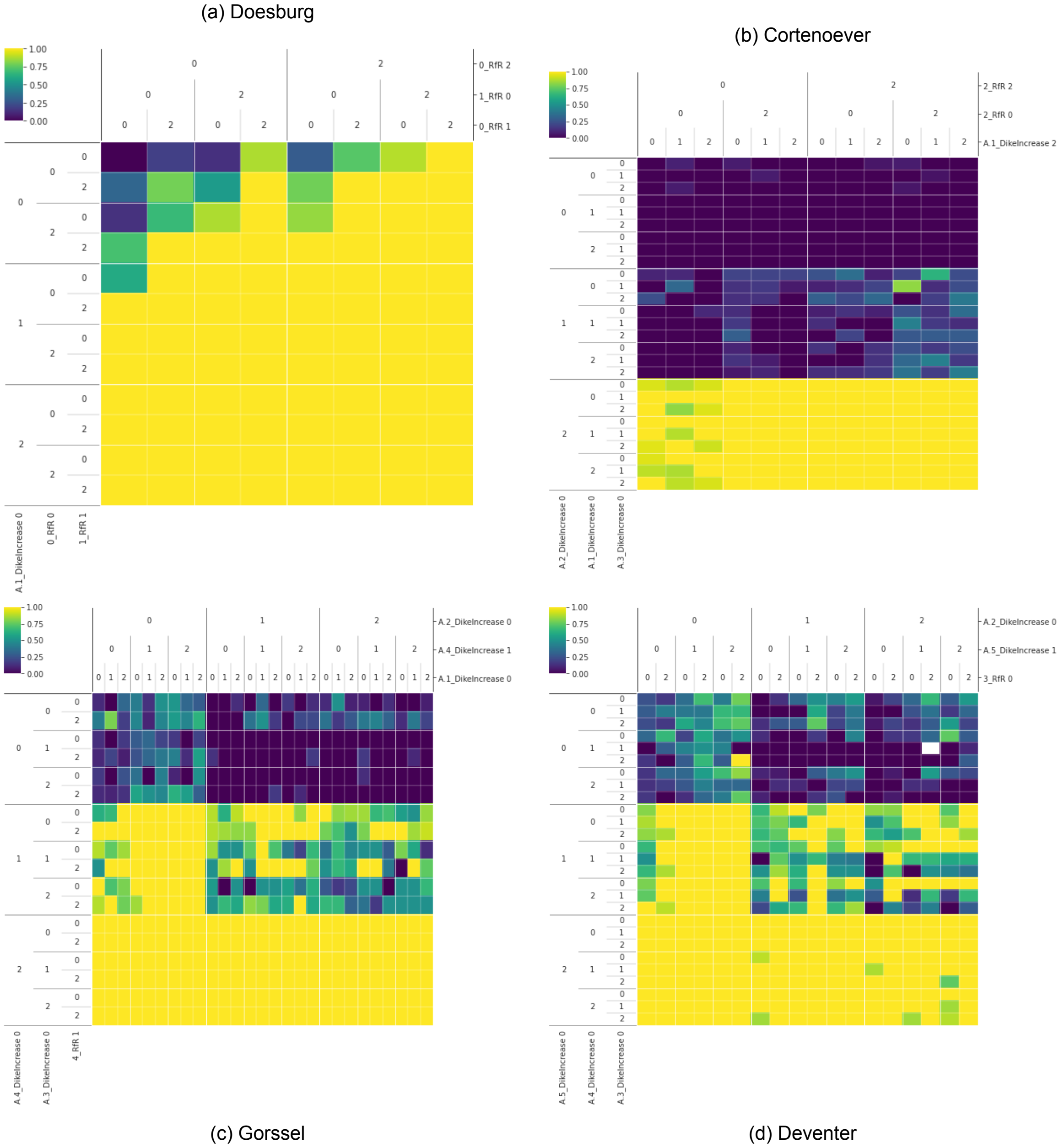
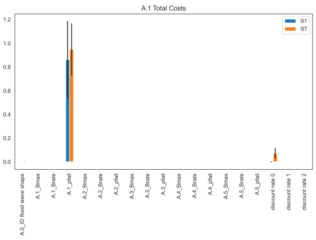


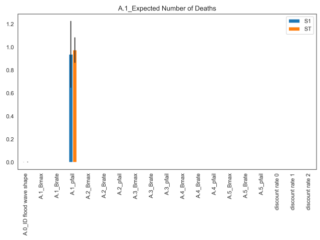
Figure B.9: Dimensional stacking of policies in the different municipalities in the pfail scenario.

B.2. Sensitivity / Vulnerability Analysis

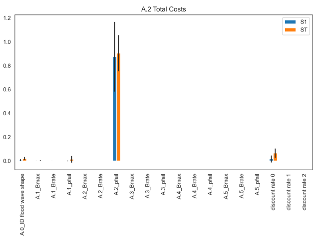
The results from SOBOL analysis for uncertainties are given below. More details on the experimental setup and interpretation of the results can be find in the section 3.1.3.



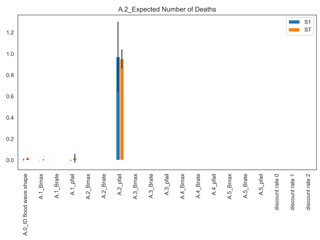
(a) Doesberg



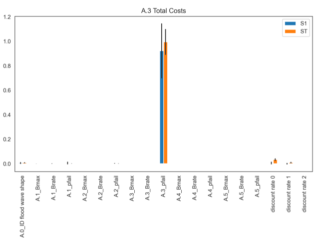
(b) Doesberg



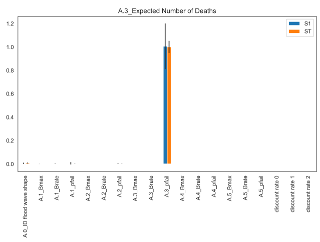
(c) Cortenoever



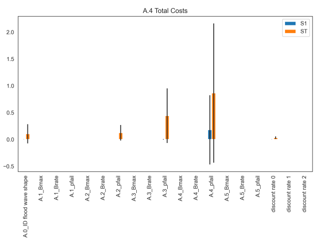
(d) Cortenoever



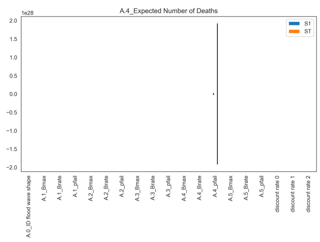
(e) Zutphen



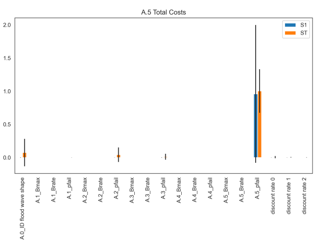
(f) Zutphen



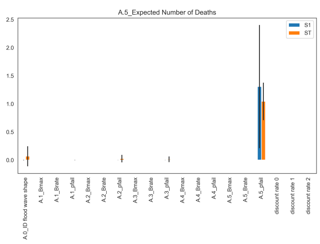
(g) Gorssel



(h) Gorssel



(i) Deventer



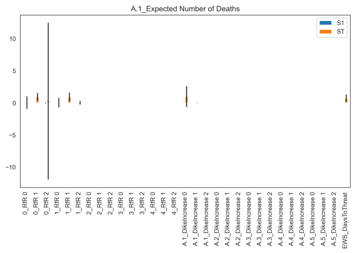
(j) Deventer

Figure B.10: Sensitivity Analysis of Uncertainties on the outcomes

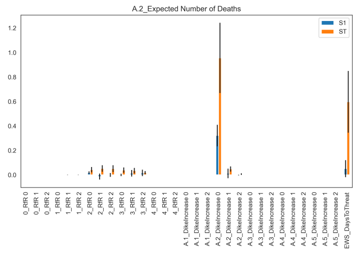
B.3. Sensitivity Analysis for Levers

This section showcases the figures illustrating key outcomes of the sensitivity analysis performed for the levers. The following feature scoring graph highlights the levers with the most influence on the given outputs (figure 3.5) .

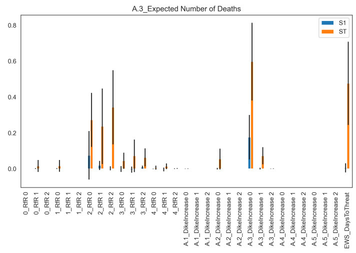
To deep dive further, the following Salib index plots should be referred (figure B.11). These plots show both first order (S1) and third-order Salib indices (ST) in blue and orange respectively. Figure B.11shows that dike heightening has the highest fist order Salib index in most of the cases. Thus dike heightening directly influences the expected number of deaths in respective regions. Apart from this, room for the river has a high third-order Salib index in most cases. This signifies that room for rivers in combination with other policy measures is also effective in reducing the expected number of deaths.



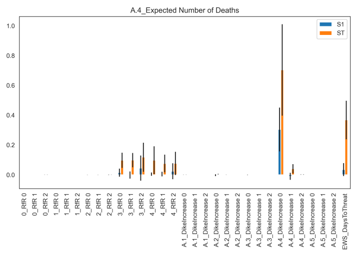
(a) Levers influencing expected number of deaths in Doesburg



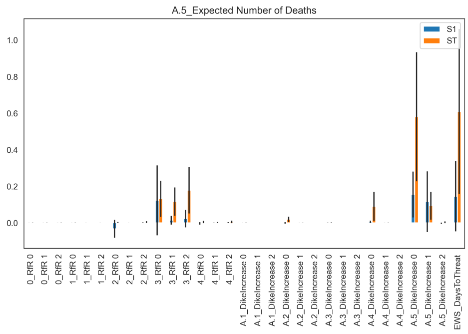
(b) Levers influencing expected number of deaths in Cortenoever



(c) Levers influencing expected number of deaths in Zupten



(d) Levers influencing expected number of deaths in Gorssel



(e) Levers influencing expected number of deaths in Deventer

Figure B.11: Levers influencing expected number of casualties in all the regions

C

Appendix C: Optimization and Robust Decision Making

C.1. Optimized Policies

There seems to be a negative correlation between deaths and dike investment costs. This can be explained by the high coo relation between dike heightening and the expected number of deaths. This figure also provides an overview of common trade-offs across solution sets. To get more insights into the trade-off, a more refined parallel axis plot is plotted for policies resulting in zero deaths in figure 3.6.

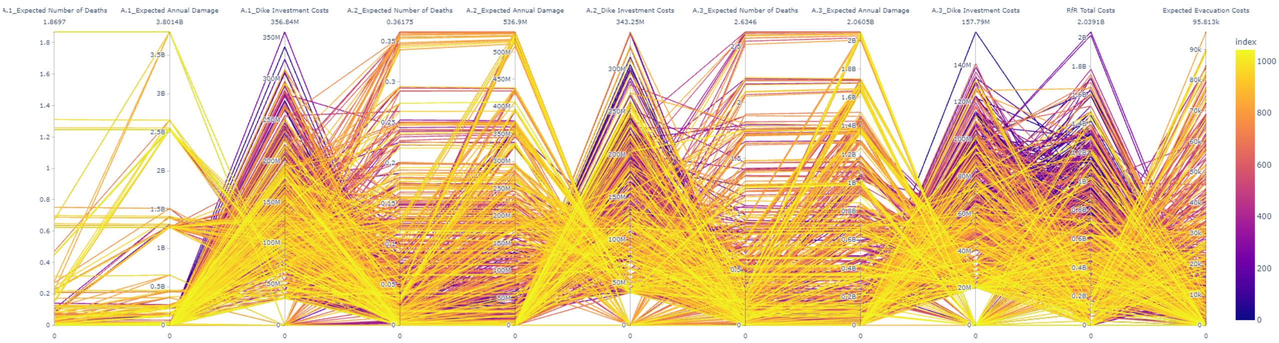


Figure C.1: Parallel Coordinate Plot: Trade-offs between outcomes for 1045 Optimized policies

C.2. Robustness Analysis

Following are the results of the Robustness analysis. Figure C.2 provides an overview of maximum regret indices of all the shortlisted policies obtained after directed search. Policies with lower regret values are preferred over those with higher regret indices. To further deep dive and compare the regret values for individual outcomes figure C.3is plotted. More details on the experimental setup are provided in section 3.2.4.

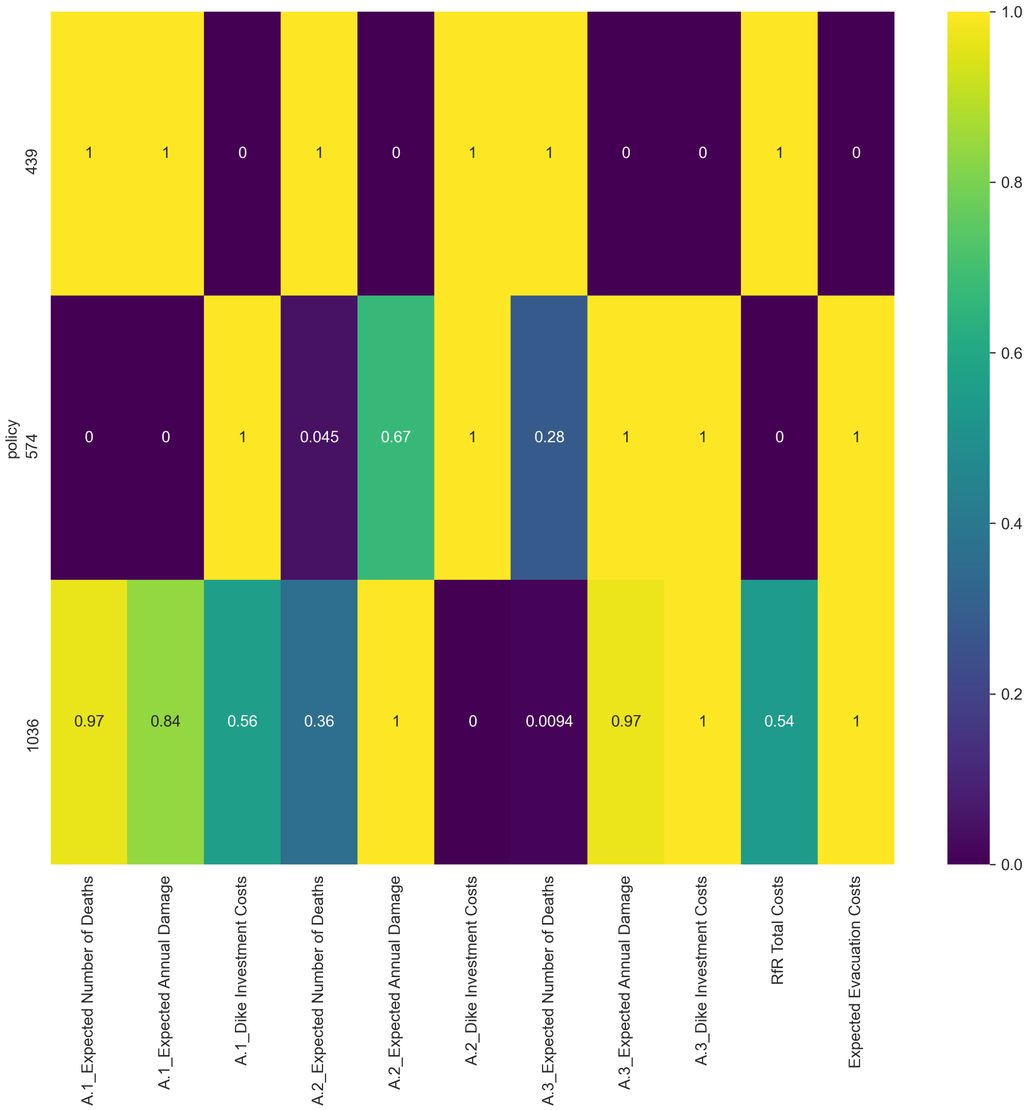
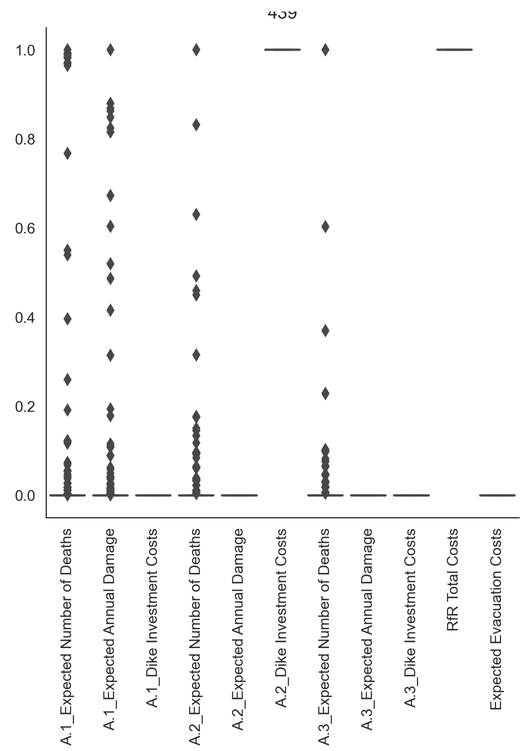
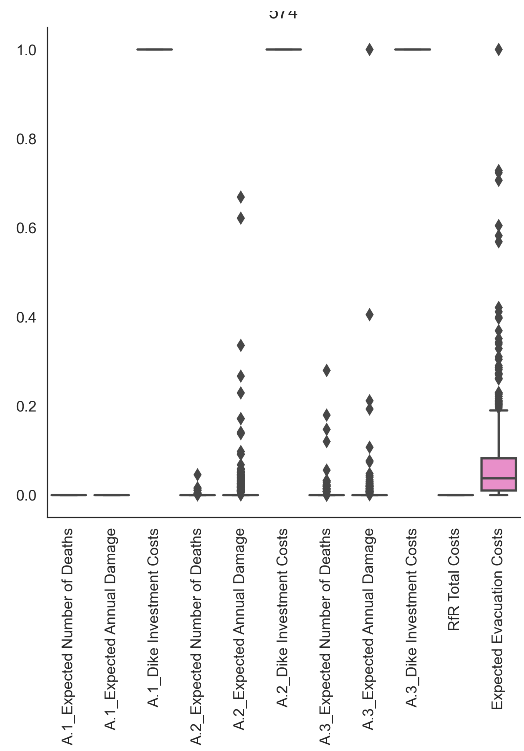


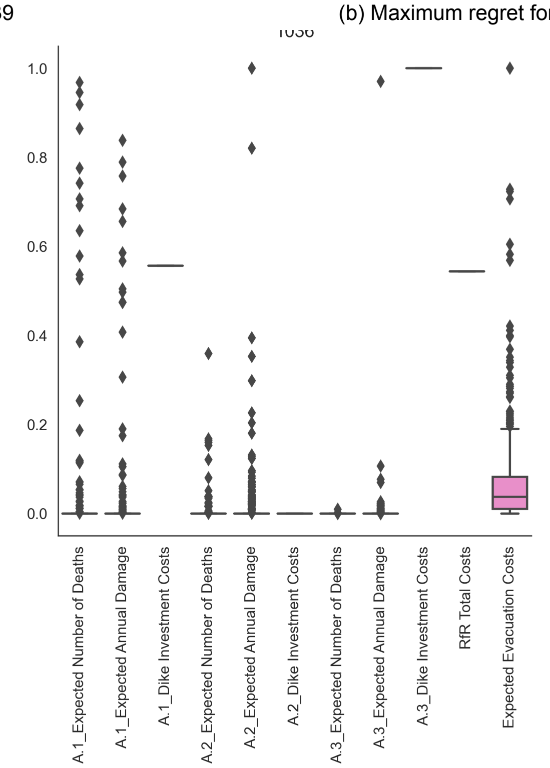
Figure C.2: Maximum regret heat map



(a) Maximum regret for policy - 439



(b) Maximum regret for policy - 574



(c) Maximum regret for policy - 1036

Figure C.3: Maximum regret of shortlisted policies for different outcomes

C.3. Scenario discovery for potential risks of proposed policy

Following are the results of scenario discovery experiments conducted for analyzing the potential risks of the proposed policy. More details on the methodology and experimental setup and result interpretation are provided in section 3.2.6.

This analysis is conducted on the results obtained by testing the policy under 1000 random scenarios. More details on this are provided in section 3.2.3. These results posed threats of high expected annual damage in Cortenoever. Thus the first analysis is focused on discovering the scenarios posing risk in the Cortenoever (figure C.4). Another open exploration with the proposed policy with random scenarios alluded towards a significant risk of expected deaths in Deventer (figure C.6). Thus, the second analysis was focused on discovering scenarios leading to the high expected number of death in Deventer.

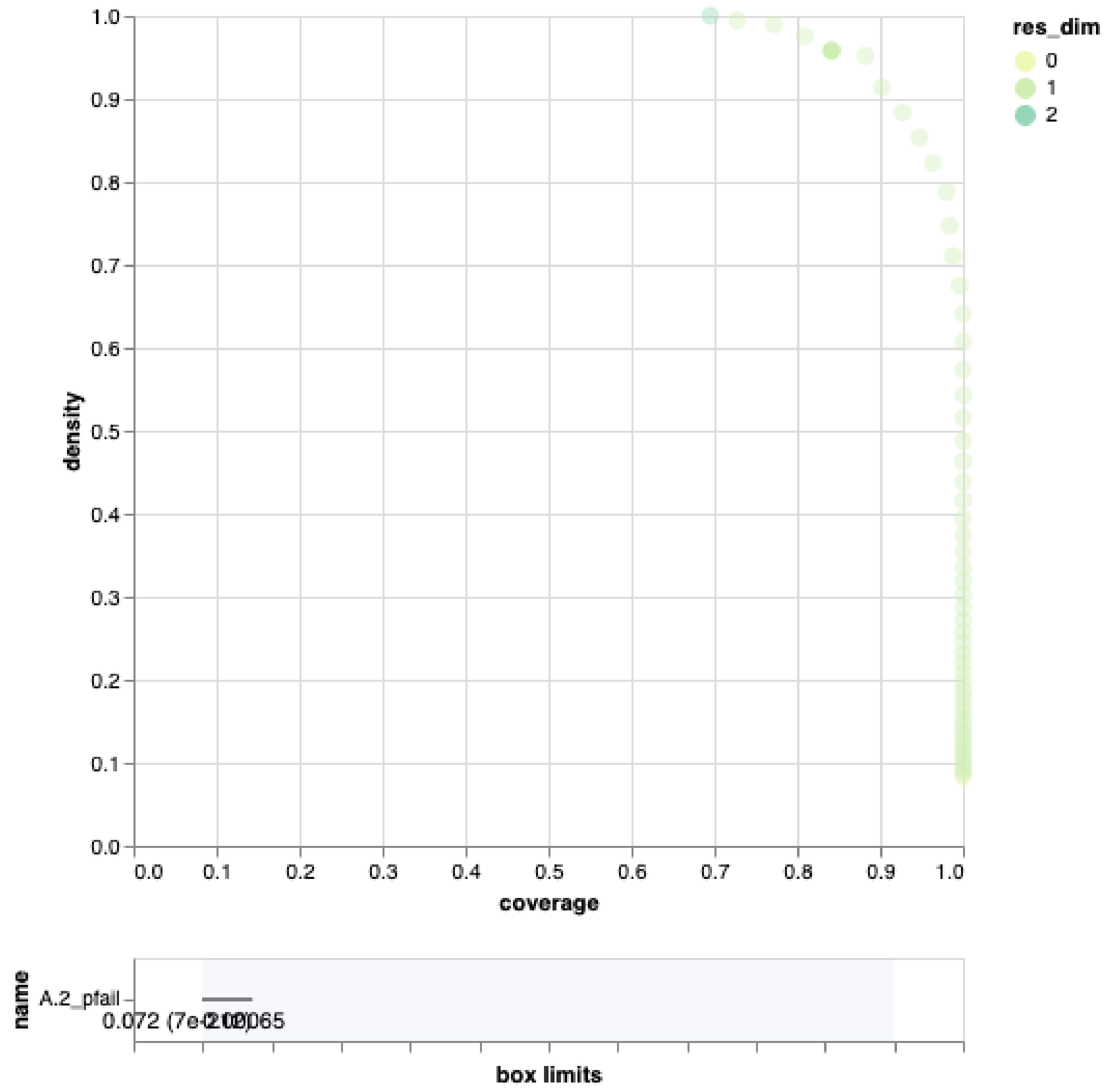


Figure C.4: Scenario discover for the potential risks of proposed policy leading to high expected annual damage in Cortenoever

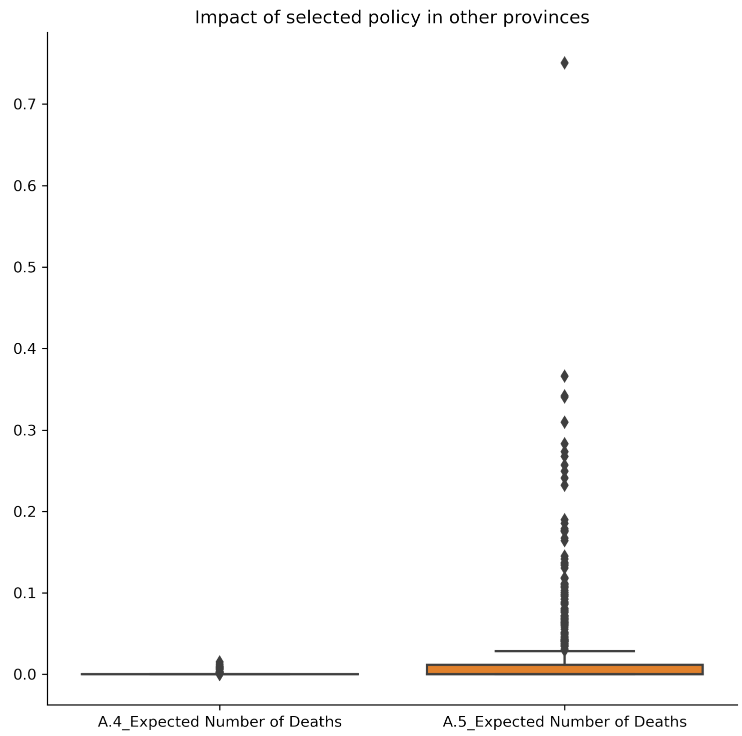


Figure C.5: Potential risks of proposed policy: Expected number of casualties in Gorssel and Deventer

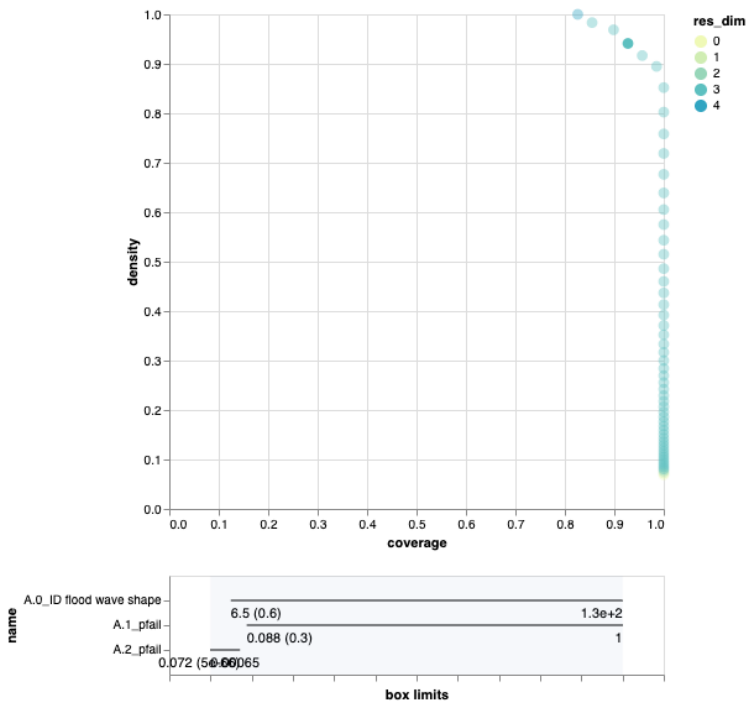


Figure C.6: Scenario discover for the potential risks of proposed policy leading to expected casualties in Deventer