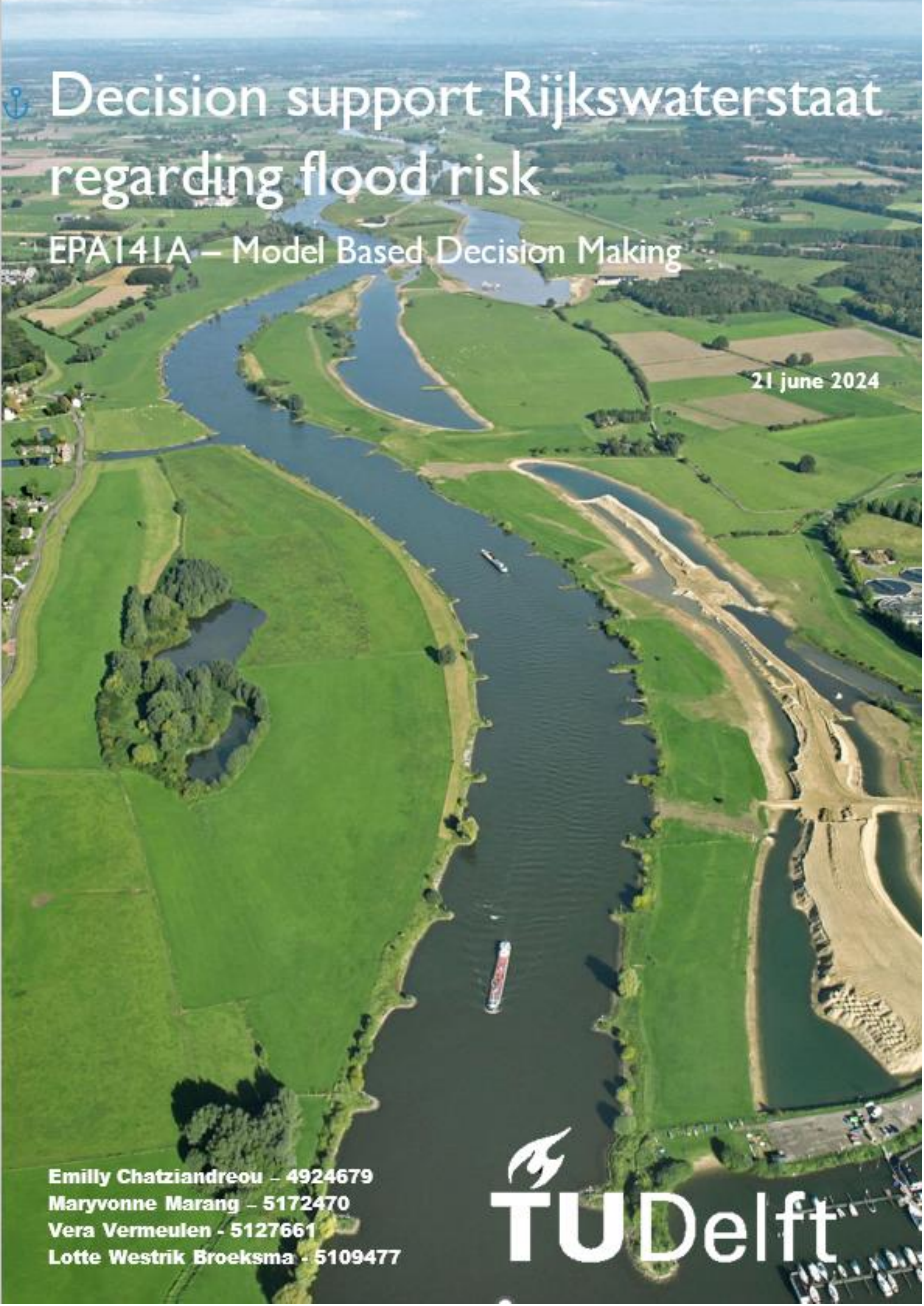

Decision support Rijkswaterstaat regarding flood risk

EPA141A – Model Based Decision Making

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Summary

This report highlights the challenges surrounding flood risk management along the IJssel, a crucial river area in the Netherlands due to its high population density and economic activities. With 59% of the Dutch territory susceptible to flooding, effective flood management is essential for safety and sustainability (Planbureau voor de Leefgeving, n.d.). Cities such as Deventer, Zutphen, and Doesburg are located within protective dike systems and play a vital role in regional development and infrastructure.

Rijkswaterstaat, under the Ministry of Infrastructure and Water Management, plays a central role in the management of flood risks in the Netherlands. The report focuses on the complex dynamics of interests and problems among the stakeholders involved, such as political actors at national and provincial levels, water managers, and environmental and transport interest groups. Central is the need to understand these different perceptions and promote a collaborative approach to develop a broadly supported strategy.

The report examines decision-making frameworks, including objectives such as minimising flood damage, preventing casualties, and adhering to budget constraints. It also includes methods to deal with deep uncertainty, such as scenario study and sensitivity analysis, to identify robust policy choices that are resilient under different future scenarios. The approach integrates multi-objective optimization to find policy measures that are both politically feasible and deliver optimal results. This structured approach presents well-founded recommendations that can help Rijkswaterstaat effectively manage flood risks along the IJssel, taking into account the diverse interests of stakeholders and deep uncertainties in decision-making.

The analysis of the results reveals a number of important points. First of all, it appears that dike rings 2 and 5 are excluded from the solution of river widening, while dike ring 1 will probably receive such a project in three of the four policy options. Dike rings 2 and 5 are in no case eligible for a river widening project. All other political non-negotiables are fulfilled. Each policy option includes at least one Room for River project, which meets the requirements of the Delta Commission. Moreover, all options ensure that there are minimal casualties, which is a strict requirement that Rijkswaterstaat itself sets. The costs of the different policy options range from 193.26 to 324.37 million euros. With the Delta Commission committing to cover 40% of the costs for one river widening project and 50% for two, the final costs for the provinces would vary between 115.95 and 162.18 million euros. Finally, it appears that the policy effects on expected damage and victims in dike rings 2, 4 and 5 are minimal with little variability. Dike ring 1 shows the highest sensitivity to these policy options, especially in terms of expected damage, which has significant implications that need to be carefully considered, especially for possible compensation to the province of Gelderland.

The four policy options discussed show that no option fully meets the wishes of the transport company, which would like to see both dike rings 3 and 5 raised by at least 5 decimetres. Each option has its own advantages and disadvantages, ranging from costs, satisfaction of interest groups such as the environment, to practical feasibility and political acceptance.

In formulating a robust and widely accepted policy design, Rijkswaterstaat should consider these results alongside political considerations.

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1. Introduction

Approximately 59% of the Netherlands' land area is susceptible to flooding, making effective flood management crucial for the country's safety and sustainability (Planbureau voor de Leefomgeving, n.d.). Among the vulnerable regions, the area surrounding the IJssel River stands out due to its significant population centres and economic activities. The IJssel, a 127 km branch of the Rhine, traverses Gelderland and Overijssel, provinces with a combined population of over 3 million people (Alle Cijfers, n.d.).
Cities like Deventer, Zutphen, and Doesburg are integral parts of this region, each situated within its protective dike system. These urban areas not only house substantial populations but also support critical infrastructure and economic activities. Ensuring their protection from floods is paramount for safeguarding lives and sustaining regional development.

Rijkswaterstaat, operating under the Ministry of Infrastructure and Water Management, plays a pivotal role in managing flood risks across the Netherlands. Flood risk management includes all efforts aimed at preventing flood events from occurring and reducing the damage caused by floods when they do happen. These measures can vary widely in terms of their costs, scope, and implications. For instance, infrastructure considerations such as building roads on top of dikes and adjusting river capacities require careful urban planning adaptations. A critical aspect of flood risk management lies in understanding and reconciling the potentially conflicting interests of upstream and downstream communities. Upstream areas typically focus on bolstering their defences against flooding, often by heightening dikes, inadvertently influencing water levels downstream. Conversely, downstream communities benefit from upstream strategies that mitigate the volume of water flowing through the river system (Ciullo et al., 2018).

Multiple stakeholders are involved in the management of the IJssel River, each with their own interests and problem perceptions. This includes political actors at national, provincial, waterboard and local levels. Additionally, the water management plan impacts environmental interest groups and transport organisations utilising the IJssel for transportation. Therefore, it is crucial for Rijkswaterstaat to map out these perceptions. A collaborative approach is necessary, considering the broader implications for the entire watershed.

This report, written by analysts from Rijkswaterstaat, explores important challenges in managing flood risks along the IJssel River. The research focuses on addressing the various concerns of stakeholders involved in making political decisions. By examining how politics and analytical models interact, the goal is to understand how they could influence policy at Rijkswaterstaat. Ultimately, this study aims to propose recommendations that help create a practical and widely supported strategy for managing risks effectively.

Firstly, the problem framework is established, exploring various approaches to structuring the decision-making problem, including identification of key objectives, constraints, and relevant factors. The methodology includes methods for handling deep uncertainty, such as scenario analysis and sensitivity analysis. The results are summarised using functional visualisations, with a focus on open exploration, policy scores at the local level, and robustness assessments at the national level. The discussion addresses the validity of the conclusions, opportunities for further refinement of the analysis, and considerations for policy recommendations within the framework of political feasibility.

2. Problem framing

To provide strategic policy advice to Rijkswaterstaat, it is crucial to thoroughly analyse the decision area, stakeholder engagement, and the uncertainties involved in the decision process. Understanding these complexities allows for tailored recommendations that address the interests of all actors in the decision arena, thereby supporting Rijkswaterstaat in achieving their objectives for flood risk management.

2.1 Objectives and constraints for flood risk management

As an analyst for Rijkswaterstaat, the primary goal is to develop an extensive flood risk management plan for the upper branch of the IJssel River. In framing this problem, several objectives and constraints are essential. The main objectives are to minimise expected annual damages (EAD), ensure zero casualties, and adhere to budget constraints. Minimising EAD involves reducing the economic impact of floods on both urban and rural areas, while ensuring zero casualties focuses on preventing loss of life during flood events. Budget constraints necessitate cost-effective solutions to satisfy stakeholders' financial concerns. Constraints include budget limitations, engineering feasibility, political acceptability, and environmental impact. Financial resources are limited, so the chosen measures must be technically viable, politically acceptable, and environmentally sustainable.

2.2 Key measures and uncertainties

To address the flood risk, several levers are under consideration. These levers include dike heightening and river widening, which is called Room for the River (RfR). Reinforcing and raising dikes can prevent breaches, while widening the river channel increases its capacity to handle higher water volumes. However, uncertainties in flood risk management stem from factors beyond the control of policymakers. Key uncertainties include the discount rate used for calculating the present-day value of damages, the shape of the incoming flood wave over time described by the A.0_ID flood wave shape, the final extent of the breach width for each dike ring, known as B_max, where greater width results in a larger volume of water entering the floodplain per unit of time, the probability that the dike will withstand the hydraulic load, referred to as pfail for each ring, and the rate at which the breach grows over time, known as Brate. These uncertainties significantly impact the feasibility and effectiveness of flood management measures, complicating the decision-making process for policymakers.

2.3 Decision area and stakeholders

The decision-making process involves actors at the local, regional, and national levels. At the national level, Rijkswaterstaat and the Delta Commission play a crucial role. Regionally, the provinces of Gelderland and Overijssel, along with three different water boards, are active. Locally, the dike rings represent the residents and surrounding farmers. Additionally, there are two interest groups affected by the decision-making process that wish to exert influence: a transport company and an environmental interest group. The relationships between these actors are depicted in Appendix A3. The five locations of interest along the IJssel River - Doesburg, Cortenoever, Zutphen, Gorssel, and Deventer - vary in urbanisation and flood risk, necessitating tailored solutions for each location. These locations are protected by dike rings, which are either urban or rural. The urban areas, such as Zutphen and Deventer, have higher population densities and more infrastructure at risk, whereas the rural areas may prioritise agricultural lands and environmental conservation.

In the final policy debate, six actors are involved: Rijkswaterstaat, the Delta Commission, two provinces, a transport company, and an environmental interest group. The provinces represent the interests of the dike rings and water boards. More information can be found in Appendices A1 and A2. The primary interests of the involved actors are:

- **Rijkswaterstaat:** As the executive agency of the Ministry of Infrastructure and Water Management, Rijkswaterstaat is responsible for developing a robust and specific policy for managing floods of the IJssel. This policy must be widely supported, preferably with the agreement of all involved actors. Additionally, Rijkswaterstaat aims to follow the political direction of the Delta Commission and therefore seeks to satisfy the Delta Commission with the new policy. It maps out the interests of various parties and facilitates negotiations and discussions to reach a consensus.
- **Delta Commission:** Like Rijkswaterstaat, the Delta Commission holds a veto right in adopting policies and is also the primary financier of the project, making actors dependent on their financial support. The Commission also oversees the National Delta Program, aimed at providing a basic level of protection behind the dikes by 2050 (Deltacommissie, n.d.). The Delta Commission emphasises long-term solutions, specific and cost-effective policy measures, and facilitates collaboration among various stakeholders.
- **Province of Overijssel:** The Province of Overijssel is located downstream of the IJssel, making cooperation and policy coordination crucial, given the potential impact of measures implemented in Gelderland without proper alignment. It is essential for Overijssel to effectively translate regional interests into national policy to ensure public acceptance. For solutions such as Room for the River (RfR), which may require residents or farmers to relocate, adequate compensation is of great importance. Additionally, the province has its own budgetary resources.
- **Province of Gelderland:** Similar to Overijssel, effective flood management policy is crucial for Gelderland. Gelderland also places significant importance on safeguarding the interests of its citizens and providing adequate compensation when necessary. The province has its own budget and, like Overijssel, strives for cost-efficiency in its policy measures.
- **Transport Company:** The stability of water levels is crucial for maintaining uninterrupted transportation flows, highlighting the transport company's interest in levee heightening policies over Room for the River (RfR). Transport companies are concerned with maintaining transport routes and infrastructure, which are vital for economic activities and mobility. Preventing disruptions in transportation networks due to flood management measures is therefore a top priority, given the potential significant economic consequences of interruptions.
- **Environmental interest group:** The environmental interest group advocates for sustainable flood management practices that protect natural habitats and biodiversity. Their focus is on ensuring that any flood risk management measures align with environmental conservation goals, preserving the ecological integrity of the river and surrounding areas. They advocate RfR-solutions, arguing that these have proven to have the most beneficial impact on nature.

The above highlights conflicting interests in this decision area. The environmental interest group and the Delta Commission primarily support RfR solutions due to their long-term effectiveness and favourable environmental impact. However, other involved parties such as the provinces are concerned about high compensation costs and public resistance to RfR, as it may require relocations. The transport company prefers dike heightenings to minimise impacts on water levels. Rijkswaterstaat must find a compromise that can garner support from all stakeholders, despite differing preferences, and utilise the budgets of the provinces and the Delta Commission effectively.

2.4 Problem framing

Framing the problem can be approached from both regional and national perspectives, each with its own set of priorities and challenges. As analyst for Rijkswaterstaat the national perspective is prioritised, focusing on the overall objective of balancing interests to keep all regions satisfied. This perspective adopts a broad view, encompassing the entire river basin and considering cumulative impact of interventions across regions. Coordinated efforts ensure consistency and maximise overall effectiveness, achieving equitable and sustainable outcomes by balancing the interests of multiple regions and stakeholders.

However, it is crucial not to overlook the regional perspective. Localised solutions tailored to the specific needs and characteristics of individual communities along the IJssel river are essential. This perspective emphasises immediate, practical measures to protect high-risk areas and minimise daily life disruption. Ignoring the regional perspective could lead to conflicts, especially if one dike ring faces significantly higher costs or more negative outcomes compared to others. While the overall national outcome might appear satisfactory, significant regional disparities could undermine the broader objectives. Therefore, ensuring that regional outcomes are also acceptable is vital to achieving a truly balanced and effective flood management strategy.

To guide the development of the flood risk management plan, the main research questions is:

> *How can Rijkswaterstaat develop an effective and sustainable flood risk management plan for the upper branch of the IJssel river that minimises expected annual damages, ensures zero casualties and adheres to budget constraints while addressing the diverse needs of stakeholders?*

By answering this question, a comprehensive flood risk management plan can be developed that meets the objectives of Rijkswaterstaat and addresses the diverse needs of all stakeholders involved.

3. Approach

3.1 Decision making under deep uncertainty

Most of the important policy decisions made today are characterised by high levels of uncertainty. Think for example about climate change; multiple different futures are possible, and there is no concrete way of figuring out what the response would be to a certain event. The traditional way of dealing with uncertainty by gathering more information and using probabilities will not work with these kinds of problems (Walker et al., 2012). There are five levels of uncertainty, the last two of which are referred to as *deep uncertainty*. The IJssel river problem discussed in this report can be characterised as a level 4 uncertainty.

‘Level 4 uncertainty represents the situation in which one is able to enumerate multiple plausible alternatives without being able to rank the alternatives in terms of perceived likelihood’ (Walker et al., 2012). This can be caused by two things; either there is a lack of knowledge about the system, or the decision makers cannot agree on the ranking. The latter is at play here. As outlined in the problem framing, the actors involved in this decision making process have different objectives and constraints, which makes it difficult to find a policy everyone agrees with. Widening the river has the preference of both the Delta Commissions and the environmental interest groups, while the provinces and the transport companies have a strong preference for making the dikes higher.

When dealing with level 4 uncertainty, the goal is to find policies that are robust - and thus work fairly well - across a range of plausible futures. Here the assumption is made that although the future is unknown, a plausible future can be specified good enough to identify policies that will result in acceptable outcomes for most stakeholders (Walker et al., 2012). In this report, this is done using Exploratory Modelling and Analysis (EMA). With EMA, insights can be gained into how the system would behave under a large variety of assumptions. The steps of the Many Objective Robust Decision (Kasprzyk et al., 2013) making have been followed through the report.

3. 2 Approach

To support Rijkswaterstaat in developing robust flood risk management policies a comprehensive approach is implemented. The analysis proceeds through several critical steps. The code used for the analysis can be found on the GitHub.

First, the top level behaviour of the system, its interactions, key uncertainties and limitations are investigated using open exploration. This involves conducting sensitivity analyses to assess the impact of uncertainties on a national level. The sensitivity analysis on both the uncertainties and possible policies results in constraints and insights on how to use the model. The base case is examined to understand the effect of uncertainties on flood risk management outcomes, and a broad set of 256 policies is evaluated to determine their effects under varying conditions. Through scenario discovery, following the sensitivity analysis, the critical scenarios on the local levels are detected. This step helps pinpoint which combinations of uncertainties are most significant for the decision-making process.

The identified critical scenarios inform the subsequent policy search. This comprehensive policy search aims to find the most effective policies across a wide range of potential future conditions. Within this policy search a multi-objective optimization process is conducted, which optimises policies to balance various levers, creating the safest and least costly combinations. During this step, constraints are set on policies based on outcomes from the debate with the different stakeholders. These constraints ensure that the number of deaths remains zero, expected annual damage is minimised and costs are kept as low as possible. The optimal policies are tested on the critical policies, to determine a final list of robust policies, according to the maximum regret metric. This comprehensive evaluation ensures that the selected policies remain effective under deep uncertainty. The culmination of these steps is the identification of a final list of robust policies that can guide Rijkswaterstaat in achieving their flood risk management objectives.

By following this structured methodology, a set of well-founded policy recommendations are provided to Rijkswaterstaat that are resilient to a wide range of future uncertainties, aligning with the national objectives. This approach ensures a balanced and sustainable strategy for flood protection, supporting Rijkswaterstaat in their mission to manage flood risks effectively.

4. Results

Following the methodology from the previous chapter, an open exploration was conducted to better understand uncertainties and policy levers. This initial phase laid the groundwork for a directed search aimed at formulating specific policy recommendations.

4.1 Open exploration

Before delving into the specifics of policy impacts, an open exploration was conducted to comprehensively assess the landscape of flood risk management. This phase aimed to uncover the intricate relationships between policy levers and uncertain parameters, providing a foundational understanding crucial for informed decision-making.

4.1.1 Policy space

The policy space analysis was conducted using 265 different policies on the reference scenario to explore their impacts on flood risk management outcomes.

In exploring the policy space using Sobol indices, complex relationships between flood risk management policies and their impacts on overall deaths and damages were revealed. Sobol indices were computed to analyse the importance and interactions of policy levers on these outcomes.
Across various policy combinations total effects consistently surpassed first-order effects, indicating significant second-order interactions among policy levers for overall deaths. This finding suggests that the combined influence of multiple policies can lead to outcomes greater than the sum of their individual impacts.
Short-term impacts (levers initiated in timestep 0) highlighted that implementing the Early Warning System (EWS) and increasing dikes at areas 3 and 5 has the most pronounced effects on reducing overall deaths. However, over the long term (levers initiated in later timesteps), the effectiveness of dike heightenings diminished, while RfR projects at locations 2 and 3 increasingly contributed to reducing overall deaths.
Similarly, Sobol indices for overall damages showed that total effects consistently exceeded first-order effects, emphasising substantial second-order interactions among policy levers. Initially, dike increases at A5 significantly reduced overall damage, but their impact declined over time, with RfR projects on location 2 and 3 becoming more influential.

Feature scoring provided insights into the overall influence of policy levers on different outcomes. Nationally, A5 dike increases and EWS days to threat emerged as primary drivers of overall damage and deaths. However, disaggregate scoring at the local level revealed that early dike heightenings at specific locations, particularly at timestep 0, significantly reduced annual damage, underscoring the critical role of timing in flood risk management.

4.1.2 Uncertainty space

The uncertainty space analysis involved 1024 scenarios with the reference policy to assess the sensitivity of flood risk management outcomes to uncertain parameters.

In the uncertainty space, Sobol indices were again utilised to explore the relative importance and interactions of uncertain parameters on overall deaths and damages. Same results can be identified for the outcome. A.1_pfail and A.3_pfail were identified as dominant parameters influencing these outcomes. Second-order effects analysis showed that combining A.1_pfail and A.3_pfail had the largest impact on the overall deaths and damages, highlighting their joint influence.

Feature scoring underscored the influence of uncertain parameters on flood risk management outcomes. At a national scale, A.1_pfail and A.3_pfail utilises substantial influence on damage and deaths outcomes. Regionally, all pfail parameters had varying impacts on expected annual damage and deaths per location, with higher uncertainty observed in the first three locations.

4.1.3 Scenario Discovery

The scenario discovery analysis involved 10,000 scenarios applied to the reference policy. The findings from this analysis are being utilised to evaluate the robustness of selected policies.Scenario discovery utilised PRIM analysis to identify the worst-case scenarios for each outcome.

For overall deaths, the most severe outcomes, constituting the top 20% worst cases in terms of the highest number of deaths, occurred when A.3_pfail was low, ranging from 0 to 0.23. This highlights the sensitivity of high mortality outcomes to a low likelihood of flood occurrence at location 3.

In terms of expected annual damage, the top 20% worst outcomes, reflecting the highest levels of damage, were observed when A.1_pfail was low, ranging between 0 and 0.35. This underscores the sensitive role of high mortality outcomes to a low likelihood of flood occurrence at location 3

The analysis extended to regional levels, focusing on each dike ring's impact on expected annual damage and overall deaths. In terms of expected annual damage, significant outcomes were observed across various locations:

- At Location 1, the analysis identified that scenarios with A.1_pfail ranging from 0 to 0.35 contributed to the highest levels of damage, representing the top 20% worst outcomes.
- Location 2 showed that an A.1_pfail between 0.27 and 1, combined with A.2_pfail from 0 to 0.28, influenced outcomes within the top 20% worst scenarios.
- Similarly, Location 3 highlighted scenarios where A.1_pfail ranged from 0.18 to 1, alongside A.3_pfail from 0 to 0.25, impacting the 20% worst outcomes.
- At Location 4, outcomes with A.1_pfail between 0.34 and 1, A.2_pfail from 0.19 to 1, A.3_pfail between 0.27 and 1, and A.4_pfail from 0 to 0.43 were notably detrimental, affecting the top 20% worst cases.
- Finally, Location 5 exhibited A.1_pfail from 0.2 to 1, A.2_pfail between 0.19 and 1, A.3_pfail from 0.27 to 1, A.4_pfail from 0.1 to 1, and A.5_pfail ranging from 0 to 0.28, all within the 20% worst outcomes.

Regarding overall deaths, the analysis identified critical scenarios across locations:

- Location 1 experienced the highest number of deaths in scenarios where A.1_pfail ranged from 0 to 0.35, representing the top 30% worst outcomes.
- Location 2 showed significant impacts with A.1_pfail between 0.27 and 1, and A.2_pfail from 0 to 0.28, influencing the 20% worst outcomes.
- In Location 3, A.1_pfail ranged from 0.18 to 1, combined with A.3_pfail from 0 to 0.25, contributing to the top 20% worst scenarios for deaths.
- Location 4 demonstrated outcomes with A.1_pfail between 0.34 and 1, A.2_pfail from 0.19 to 1, A.3_pfail between 0.27 and 1, and A.4_pfail from 0 to 0.43, impacting the 20% worst cases.
- Location 5 reflected scenarios with A.1_pfail from 0.11 to 1, A.2_pfail between 0.19 and 1, A.3_pfail from 0.27 to 1, A.4_pfail from 0.1 to 1, and A.5_pfail from 0 to 0.26, all within the 20% worst outcomes.

The aggregated results from these regional analyses were compiled into a comprehensive CSV file. This dataset will serve as a critical tool for evaluating and refining optimal policies identified through directed search with constraints, ensuring robust decision-making in flood risk management strategies. By leveraging these insights, stakeholders can prioritise interventions that effectively mitigate risks and enhance resilience in vulnerable regions.

4.2 Policy search

The search for an appropriate policy consists of three distinct parts. First, the optimise function in the EMA-workbench is used for a directed search approach, to optimise a large number of policies based on the reference scenario. These policies are narrowed down by taking out those who do not meet the policial non negotiables. The policies that are left will undergo a robustness assessment over the critical scenarios identified in the scenario discovery.

4.2.1 Directed search

Where the open exploration was run on the supercomputer of the TU Delft, Delft Blue, the directed search part of this analysis was done on the laptops of the analyst themselves. The waiting times on the super computer had gotten so long, that it was no longer possible to finish these bigger runs on time. To decrease the computational power needed, the optimization is run using a different problem formulation. As Rijkswaterstaat is a national entity, the policies are only optimised for the aggregate results of costs, damages and deaths. To further minimise the computational power needed, the optimization was done using only the first timestep, eliminating the possibility to look at adaptive pathways further down the line.

Two components are important when running optimization; the number of functional evaluations (nfe) and the epsilon. The higher the number of functional evaluations, the more potential policies that will be assessed. The epsilon represents the granularity of the grid imposed on the objective space. The smaller the epsilon, the smaller the grids, and thus the more solutions will be maintained in the optimised set. It does however slow down the optimization. The epsilon is also used to check whether or not the MOEA has converted to the optimum solutions.

Two different optimizations have been run; one with 50k functional evaluations and one with 100k. Both have the same epsilon value of 0.01, and have been run over the reference policy. The first run resulted in 315 possible policies, but was not fully converged yet. The larger optimization resulted in 381 plausible policies, while being further in the convergence.

4.2.2 Policy constraints and selection

Based on the conversations Rijkswaterstaat had with the stakeholders involved, as well as the debates had, a few political no-go's were identified. These non-negotiables were used to narrow down the identified optimal policies into politically viable recommendations.

The most important constraint came from Rijkswaterstaat themselves, being that the expected annual deaths should be zero. Coincidentally, this also minimises the expected annual damage. The Delta commission wants to see at least one Room-for-River project. So much so, that they are willing to contribute more if it is part of the recommended policy. Due to budget constraints caused by the provinces and the promise of the Delta Commission to pay half of the proposal if it happens, the goal is to get two RfR projects in the optimised policy.

Rijkswaterstaat is aiming for a 6-0 vote in favour of the suggested policy. However, as safety is the main priority of Rijkswaterstaat and longevity (translated into a RfR preference) is the priority of Delta having the budget. The provinces plead for safety and as little damage as possible, having a budget of their own to contribute with a preference for dike heightenings. In order to get the transport company and the environmental interest group to agree on the proposed policies, their preferences will be taken into account as much as possible. However, as they both have low power (see problem framing), their preferences will not be treated as political non-negotiables. The transport company wants to increase dike 3 and 5 with at least 5 decimeter, and the environmental interest group wants as many Room for River projects as possible. The preferences of the environmental groups are also supported by the goals of Delta. The transport's group preference for dike heightenings is shared with the Provinces.

Table 1: Resulting policies after the constraints

Constraint	Optimization run - 50k	Optimization run - 100k
Rijkswaterstaat	37	40
Rijkswaterstaat + Delta Commission	33	34
Rijkswaterstaat + Delta Commission + Transport company - both dikes	0	0
Rijkswaterstaat + Delta Commission + Transport company - one dike	1	1
Rijkswaterstaat + Delta Commission + no damage	5	6

4.3 Robustness assessment

The policies resulting from the optimization have not yet been tested on effectiveness in other scenarios then they were discovered. To assess whether or not they would result in acceptable outcomes in multiple different futures, a robustness assessment was conducted. Using the 10k critical scenarios resulting from the scenario discovery and the six plausible policies originated from the large directed search, another MOEA is run. The robustness of the possible policies will be calculated using the maximum-regret metric.

As analysts for Rijkswaterstaat, the most important outcomes are the aggregated/ national ones. However, to ensure that the concerns of the local levels are not dismissed, the critical regional scenarios are used to evaluate the robustness of the most optimal national policies. In extension, the policies are tested by the disaggregated problem formulation, as opposed to the aggregated version used during the optimization.

Maximum regret

With regret based metrics, the difference of the performance of a particular policy and the performance of the best possible policy represent the regret of the decision alternative (McPhail at al., 2018). A robust decision is the one that minimises the maximum regret, making the ranking highly risk averse (Herman at al., 2015 in McPhail at al., 2018).

When looking at the tradeoff plot in figure XXX, it becomes clear that none of the policies resulting from the optimization scores good on all three outcomes at the same time when running them in the worst-case scenarios for the regional levels. Policies that score well on the costs and expected casualties, generally result in high damage and vice versa. What is especially interesting to see is that even though the policies were optimised to not exceed more than 0.001 expected number of deaths per year, in the worst-case scenario, this does happen.

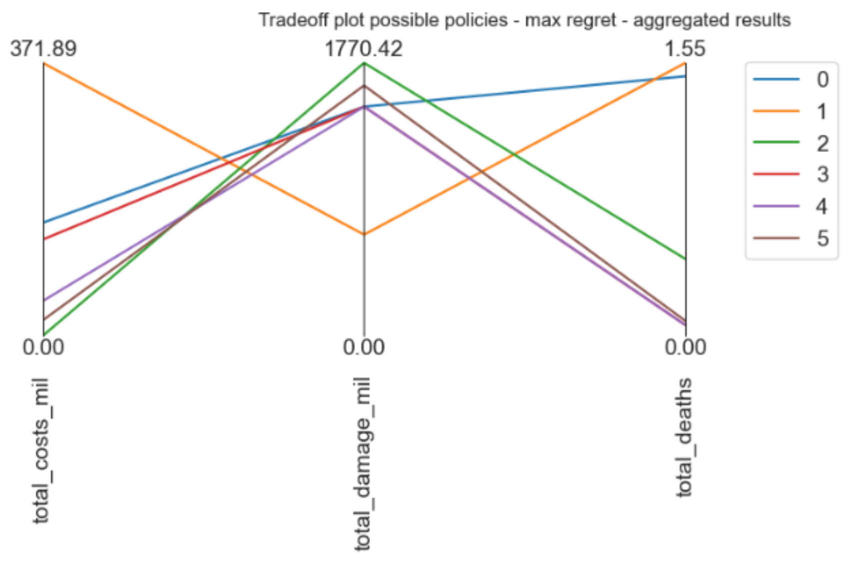

Figure 1: Trade Off plot - maximum regret

Minimising the possible casualties is a non negotiable for Rijkswaterstaat, therefore it is important to take a closer look at them. As it turns out, when looking at what policies are expected to result in more than one casualty due to flood, only two of them emerged. Policy 0 78 times, and policy 1 71 times. It was therefore decided to remove these two policies from further analysis.

Final list of robust policies

From all of the possible policies run, four of them remained in the final list of robust policies (see the table below for details). What is interesting to see is that Dike-ring 2 and 5 will never get a Room for River project, and Dike-ring 1 will almost always get one. The requirement from the transport company to increase both Dike-rings 3 and 5 with at least 5 decimeter is not possible. However, the other political non-negotiables are met. With the promise to pay 40% of the proposal with one Room-for-River project, and 50% with two, the final costs for the, this would leave the costs for the provinces at 115.95-162.18 million euros.

Table 2: List of final robust policies

			Room for River project					Dike Increase						
Policy - name	Policy - robustness	Policy - optimization	1	2	3	4	5	1	2	3	4	5	Early Warning System [Days]	Total costs [million €]
Lowest costs - highest deaths	2	223	0	0	1	0	0	2	4	3	5	5	1	193.26
Higher costs - lower damage and deaths	3	227	1	0	0	1	0	0	4	4	3	3	3	324.37
Lowest overall maximum regret	4	288	1	0	1	0	0	0	4	3	5	5	3	240.60
Highest expected damage	5	373	1	0	0	0	0	0	4	4	4	6	2	214.33

The next step for Rijkswaterstaat is to present these policies to the stakeholders. As it is important for them to know the distribution of costs over the dikerings and thus the provinces. When looking at the cluster boxplots in Appendix XXX, it becomes clear that the influence of each policy on both the expected damage and number of deaths in Dikering 2, 4 and 5 is very small, with minimal distribution. Dikering 1 is the most influenced by the policies. Especially for the expected damage, the general importance is high, combined with a large tail. Careful consideration must be given as to how this might affect possible compensation to the province of Gelderland.

5. Discussion

The complexity presented in the case of the IJssel river, reinforced by the multi-actor nature of policy debates in political arenas, requires an extended discussion on the outcomes.The limitations and reflections on the approach and findings of this research presented in the following paragraphs, function as guidance for Rijkswaterstaat in an objective interpretation of the results, a further advancement of the research and a successful implementation of a policy design.

5.1 Model Limitations en Recommendations

In order for the findings to be interpreted correctly, it is important to reflect on the use of the model and the underlying assumptions. The model used in this analysis considers a time-period of 100 years, and knows a static number of flood events over this period. As mentioned by Delta in the early debates, uncertainties about the evolution of climate change effects may impact the frequency with which these events occur, altering the outcomes of interests for different policies. Ideally, different scenarios regarding an increasing occurrence of flood phenomena should be considered in order to further reflect on the robustness of policies on a climate adaptation level. Computational power constraints however discouraged this additional analysis. Reflecting on climate change radicalisation can boost the policy designs on long-term robustness promoting alternatives that can deal with different degrees of natural effects on the system, limiting the effect of seasonal uncertainty.

Optimization was conducted on an aggregate problem formulation due to computational limitations, which may oversimplify regional objectives and compromised accuracy. Preferably, the optimization should be run over the disaggregated results considering the regional objectives in a more equitable manner. However, optimising over a large number of outcomes requires a large amount of computational power in order to achieve convergence. It is recommended to optimise over the damage and death outcomes of the different dikes to ensure regional safety and political acceptance of the suggested policy.

Another aspect limited in the current approach is proper seed management. In each instantiation of the model random values are assigned to input variables. Systematically interchanging the seed from which these pseudo-random values originate would provide a better coverage of the possible outcomes. By doing so, uncertainty due to reliance on random values is limited, offering more trustworthy results that can be presented with higher confidence, limiting undesirable and unexpected outcomes.

5.2 Future Adaptive Policies

Having assessed different policies over scenarios responsible for undesirable outcomes we can already somewhat assess their robustness. In reality, this approach comes short considering deep uncertainties such as climate change, future legislation frameworks and yet-to-be political arenas. The assessment reflecting the current sensitivities and uncertainties with the present-day stakeholders may seem unviable in the long-term. Dynamic approaches can alleviate this high degree of uncertainty, assessing the future in shorter, more distinct periods over which assumptions can be reconsidered with actual information. This approach

(Haasnoot et al., 2013) is called Dynamic Adaptation Policy Pathways (DAPP) and accounts for changes in the decision-making context by identifying different tipping points during which the planning can be adjusted to actualised model input.

Methodologically, future refinements should incorporate varying time steps and policy levers within the model settings to simulate adaptive pathways effectively. Moreover, exploring multiple optimization scenarios with different starting conditions can mitigate the impacts of stochasticity, although at increased computational costs and time requirements. The adaptive policy approach results into policy designs more flexible to future uncertainties by postponing the decision moment until more information with a smaller uncertainty degree is available and thus is highly recommended despite the above mentioned costs.

5.3 Policy designs and implications

Chapter 4.3 discusses four policy options with regard to water safety. None of these options fully meets the wishes of the transport company, which would like to see both dike rings 3 and 5 raised by at least 5 decimeters.

The first policy, "low costs - highest deaths," includes only one Room for the River. As a result, the Delta Commission will be less satisfied and may finance less. The environmental interest group will also feel some disappointment. However, this policy has the lowest costs, which is beneficial for the provinces.

The second policy, "higher costs - lower damage and deaths," includes two Room for the Rivers, which satisfies both the Delta Commission and the environmental interest group. However, this policy is the most expensive, which is a negative point for the provinces. In addition, additional costs may have to be incurred to buy out farmers and local residents along the Room for the River.

The third policy, "lowest overall maximum regret," again includes two Room for the Rivers, which is favourable to the environmental group and the Delta Commission. In addition, dike ring 5 will be raised here by 5 decimeters, which may mean some acceptance for the transport company. The costs of this policy fall in the mid-range of all options, which may provide some relief for provinces. The Delta Commission also increases its budget if two Rooms for the Rivers are realised, as is the case in this policy.

The fourth policy, "highest expected damage," again contains only one Room for the River. As a result, both the Delta Commission and the environmental interest group are not completely satisfied. This policy may be more attractive for the transport company, because dikes 3 and 5 here come closest to their desired height.

5.4 Interpretation in a political dimension

Due to the complexity of model-based decision making in political arenas where national and regional parties, with differing views and goals have to form a consensus it is very important to reflect on the effect of this context on the findings of this report. This political decision making arena reflects on many more aspects apart from methodological and computational validity and accuracy.

As described by Steinbach (2022) politicians often view analyses as support of already made decisions. Cherry-picking of policy designs, assumptions or methodologies can result into misinterpretation or misuse of results for political benefit. An example of this is the agnostic view some stakeholders have with regards to data-driven modelling. This can cause some actors to dismiss the complete model or modelling as an approach instead of showing willingness to include insights provided as discussion points. The environmental group openly admitted to not trust the model outcomes as they did not account for environmental and ecological issues.

Factors forming the current political context should also be taken into account. Political considerations rushing the decision making process to keep voters happy (upcoming elections in the province of Overijssel) or demeaning, if not completely disregarding long-term effects, for personal political association with the tangible short-term results. A transparent but concise communication of the trade-offs introduced in the model for the analysis and an incorporation of an adaptive policy pathway can help mitigate these issues, dividing the decision-making period into concrete timesteps. This easens the distribution of responsibility and conceptualises it, making it easier for politicians to navigate through the debates and discussions (Sienknecht & Vetterlein, 2023).

6. Conclusions

In conclusion, Rijkswaterstaat plays a central role in flood risk management in the Netherlands, with various measures and policy options being considered. This ranges from raising dikes to widening rivers, all within the context of urban planning and political feasibility. The decision-making process around the IJssel involves numerous stakeholders, including actors operating at national, regional and local level, as well as environmental interest groups and transport companies. A collaborative approach is necessary to take into account the wider implications for the entire catchment.

From a national perspective, Rijkswaterstaat focuses on developing an integrated strategy for the entire IJssel river basin. This perspective seeks to balance the interests of all regions and ensure a coherent and efficient approach that maximises overall security and sustainability. The regional perspective emphasises specific, local needs and circumstances along the IJssel. This approach emphasises immediate, practical measures to protect high-risk areas and minimise disruption to daily life. Ignoring the regional perspective can lead to conflict. The central question in this report therefore is: *How can Rijkswaterstaat develop an effective and sustainable flood risk management plan for the upper branch of the IJssel river that minimises expected annual damages, ensures zero casualties and adheres to budget constraints while addressing the diverse needs of stakeholders?*

To answer this question, several model-based analyses have been conducted. Four robust policy options have been identified after a thorough robustness assessment under various scenarios. These policies are:

- **Lowest cost-highest deaths**: with this policy there is one Room for the River (dike ring 3), furthermore dike ring 1 to 5 are increased by 2, 4, 3, 5 and dm respectively. This policy has a cost of 193.26 million euros, and is therefore the cheapest. The option with only one Room for the River project leads to less satisfaction with the Delta Commission, which may result in lower financing. Environmental interest groups will also be disappointed. Nevertheless, the cost of this option is the lowest, which is beneficial for the provinces.
- **Higher costs-lower damage and deaths:** there are two Rom for River's (dike ring 1 and 4). In addition, dike increases of dike ring 2 to 5, by 4, 4, 3 and 3 dm respectively. This policy has a cost of 324.37 million euros, and is therefore the most expensive. The option with two Room for the River projects complies with both the Delta Commission and the environmental interest groups. However, it is the most expensive option, which is disadvantageous for the provinces. In addition, additional costs may arise for buying out farmers and local residents along the Room for the River projects.
- **Lowest overall maximum regret:** there are two Room for River's (dike ring 1 and 3). In addition, dike increases of dike ring 2 to 5, by 4, 3, 5 and 5 dm respectively. The option with two Room for the River projects is good for the environmental interest group and the Delta Commission. Dike ring 5 will be raised by 5 decimeters, which can promote acceptance by the transport company. The costs fall in the mid-range of all options, with possible relief for the provinces.
- **Highest expected damage:** with this policy there is one Room for the River (dike ring 1), furthermore dike ring 1 to 5 are increased by 4, 4, 4 and 6 dm respectively. All in all, only one includes Room for the River, which does not fully comply with the Delta

Commission and environmental interest groups. However, it may be more attractive for the transport company due to its proximity to the desired height of dikes 3 and 5.

A number of things can be noted from the analysis of these results:

- First, dike rings 2 and 5 are excluded from the Room for River project, whereas dike ring 1 is highly likely to receive one**.** Of the four final policy options, dike ring 1 has a 'Room for the River' project in three cases, while dike ring 2 and 5 do not have a 'Room for the River' project in any case.
- Furthermore, meeting the transport company's requirement to increase Dike-rings 3 and 5 by at least 5 decimeters is not feasible. This means that this requirement of the transport company is most likely not realistic. Rijkswaterstaat will have to communicate this openly.
- All other political non-negotiables are satisfied. Each policy includes at least one Room for the River project, meeting the requirements of the Delta Commission. Additionally, each policy ensures zero casualties, which is a strict requirement set by Rijkswaterstaat itself.
- The costs of the policies vary from 193.26 to 324.37 million euros. With the Delta Commission committing to cover 40% of the costs with one Room-for-River project and 50% with two, the final expenses for the provinces would range between 115.95 and 162.18 million euros.
- Lastly, the policy impact on expected damage and fatalities in Dike-rings 2, 4, and 5 is minimal with insignificant variability. Dike-ring 1 shows the highest **sensitivity** to these policies, particularly in expected damage, with significant implications that require careful consideration for potential compensation to Gelderland province.

To correctly interpret the findings, critical reflection on the use of the model and the underlying assumptions is essential. The model, which includes a 100-year period and a static number of flood events, may be affected by uncertainties in the evolution of climate change, which may change outcomes for policy measures. It is recommended to consider different scenarios of increasing flood frequencies to further investigate the robustness of climate adaptation policies, although this is complicated by computer capacity limitations.

Optimising policy measures, such as Rijkswaterstaat, requires a more detailed approach that more accurately reflects regional objectives. Furthermore, improving the management of random input variables within the model is crucial to obtain more reliable results and minimise unexpected outcomes.

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Appendix A - Stakeholder Analysis

A.1 Power-Interest Grid

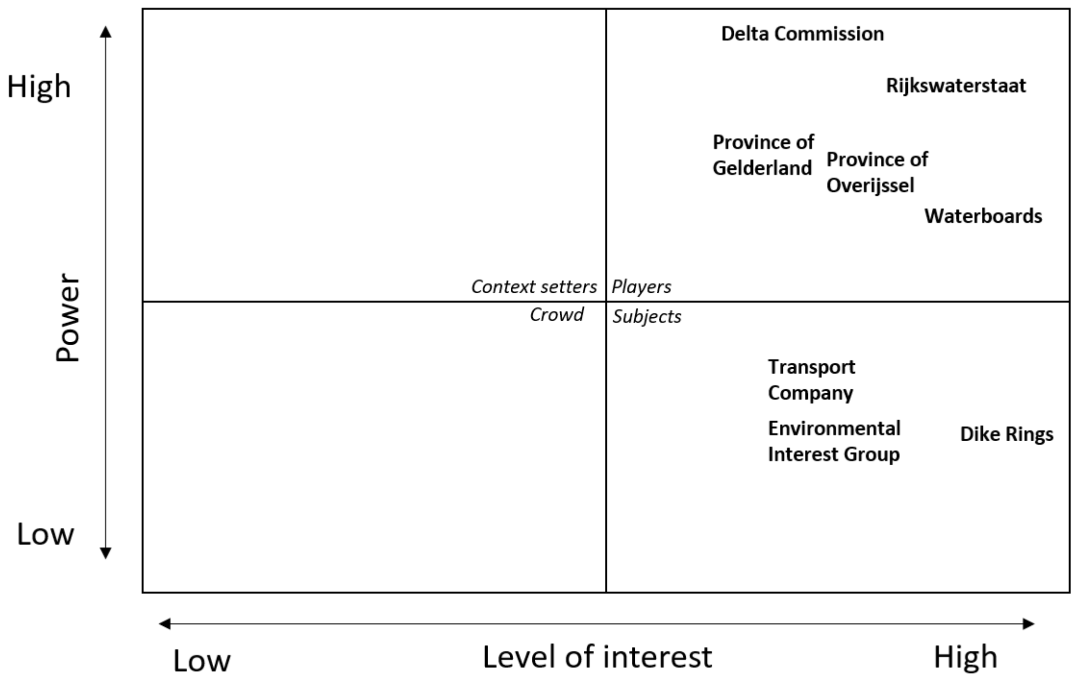

Figure A.1 - Power-interst Grid

Players
The national water management organisation, Rijkswaterstaat, is a very influential actor in water management. This agency holds significant political influence as the executive body of the Ministry of Infrastructure and Water Management. Rijkswaterstaat is tasked with developing policies to prevent flooding. Moreover, Rijkswaterstaat itself has a keen interest in effective flood prevention policies, as it is responsible for managing large bodies of water such as rivers (Rijkswaterstaat, n.d.). They are tasked, among other things, with ensuring that floods do not occur.

The Delta Commission has the most influence on policy decisions. They have a veto right in decisions about adopting policies. Despite Rijkswaterstaat initially seeming to have the greatest influence by proposing policies, Rijkswaterstaat must follow the political course set by the Delta Commission. Additionally, the Delta Commission is the primary financier of the project, making future policies largely dependent on their financial resources. Furthermore, the Delta Commission has a significant interest in a comprehensive flood protection plan around the IJssel. They are responsible for implementing the National Delta Program, where water safety is a crucial component. By 2050, the Delta Program aims for everyone behind the dikes to have a basic level of protection, meaning the chance of death from a flood should not exceed once in every 100,000 years (Deltaprogramma, 2024).

The provinces also have considerable power. It is crucial that they agree with the policy due to their financial resources. Additionally, provinces have authority over permits and spatial planning within their territories (Informatiepunt Leefomgeving, n.d.). Gelderland holds slightly more influence than Overijssel because it is located in the upstream area of the IJssel River (Erfgoed Gelderland, n.d.). Measures taken by Gelderland impact Overijssel, but not vice versa. Furthermore, the budget allocated to provinces from the Provincial Fund is partly determined by their population size (Prodemos, n.d.). Gelderland has significantly more residents than Overijssel, thus enjoying a larger budget (Alle Cijfers, n.d.). Both provinces place great importance on effective flood risk policies. They are responsible for translating the national framework for water management policy into regional policies (Ministry of Infrastructure and Water Management, n.d.).It is crucial for them to translate the interests of residents and other stakeholders into national policies to ensure public acceptance. Overijssel has a slightly greater stake in the issue as it lies in the downstream area of the river. Therefore, effective policy coordination is crucial for them, as measures taken by Gelderland could adversely affect them without proper alignment.

Finally, water boards also have significant power and importance. They are responsible for operational water management, setting conditions to achieve strategic water management goals, determining concrete measures, and implementing them (Ministerie van infrastructuur en waterstaat, n.d.). Water boards regulate water levels through structures such as locks and pumping stations, and protect the land from flooding (Rijksoverheid, n.d.). Water boards collaborate closely with provinces, and their interests largely align (Unie van Waterschappen, 2021).

Subjects

The transport company has considerably less power. It is unable to directly influence policy, this can only be done indirectly through advocating. The transport company does have a budget, but it is difficult to utilise due to legal constraints related to public-private partnerships. It could be argued, however, that the transport company enjoys slightly more power compared to environmental interest group because it contributes to the Dutch economy, potentially giving it a stronger negotiating position. The transport company also has a stake in the issue since water levels affect transportation possibilities along the river.

The environmental interest group can also only influence through advocacy. They have a significant stake because the policy being formed will have long-term impacts. Therefore, it is crucial for them that environmental considerations are integrated into this process. However, this case concerns only one specific project, whereas the environmental interest group deals with environmental issues spanning multiple matters, which somewhat limits their direct relevance.

Similarly, the Dike Rings rely solely on advocacy as well. They do have a substantial interest in the issue at hand. Residents living within the dike rings or farmers operating their businesses there are directly affected by the policy being shaped.

A.2 Interest, Objectives, Possible Actions Of Relevant Actors

Table A.2 - Actor, Interest, Objective, Possible Actions

Actor	Interest	Objective	Possible Actions
Delta Commission	● Successful implementation of the Delta Plan ● Protecting the Netherlands against floods, ensuring sufficient freshwater availability, and contributing to a climate-resilient and water-robust infrastructure (Deltacommissie n.d.)	● Emphasising the importance of long-term solutions for the IJssel River ● Implementing specific, robust, and financially efficient policies	● Acting as a facilitator to bring together various stakeholders and actors to achieve consensus ● Providing financial resources for the project ● Making concrete recommendations and policy proposals
Rijkswaterstaat	● Managing and developing national roads, waterways, and waters (Rijkswaterstaat, n.d.) ● Promoting a sustainable living environment (Rijkswaterstaat, n.d.)	● Developing a robust and specific policy for managing floods of the IJssel river. ● Developing policy supported by all stakeholders.	● Making policy proposals ● Mapping the interests of other stakeholders ● Facilitating negotiations and discussions among all involved actors
Province of Gelderland	● Healthy, safe, clean, and prosperous Gelderland (Province of Gelderland, n.d.) ● Commitment to clean water, sufficient drinking water, and preventing floods in the Gelderland regions (Province of Gelderland, n.d.).	● Representing the interests of regions with dike rings, both in rural and urban areas ● Ensuring safety for residents of the province of Gelderland ● Creating policies that do not unnecessarily restrict economic freedom ● Preference for dike heightening	● Providing financial budgets ● Making policy proposals ● Engaging in collaborations with other stakeholders

Provincie Overijssel	• That everyone can live, work, and recreate in a healthy and enjoyable environment in the province (Werken bij Overijssel, n.d.). • Improving water safety and the living and working environment (Province of Overijssel, n.d.).	• Representing the interests of municipalities with dike rings and lobbying effectively for their positions • Ensuring safety for residents of the province of Overijssel • Fair policies where each party shares in the responsibility • Preference for dike heightening	• Providing financial budgets • Making policy proposals • Engaging in collaborations with other stakeholders
Waterboards	• Effective regional water management • Effective protection against floods in the Netherlands	• Implementing effective measures to lower water levels in the IJssel river during periods of heavy rain • Maintaining good water quality in the IJssel river	• Engaging in collaborations with other stakeholders • Making policy proposals • Advocating policy proposals to Rijkswaterstaat
Transport Company	• Making a profit	• Ensuring that the water levels in the IJssel river remain relatively stable to facilitate smooth transportation along the river • Preference for dike heightening	• Engaging in collaborations with other stakeholders • Advocating
Environmental Interest Group	• Preventing environmental damage	• Promoting room for the river options • Incorporating environmental outcomes in policy that are challenging to measure in a model	• Engaging in collaborations with other stakeholders • Advocating
Dike Rings	• A safe living environment for both residential living and agricultural operations	• Low risk of flooding from the IJssel river • No adverse impact on the living environment due to policy measures	• Engaging in collaborations with other stakeholders • Advocating • Protest at provinces

A.3 Formal Chart

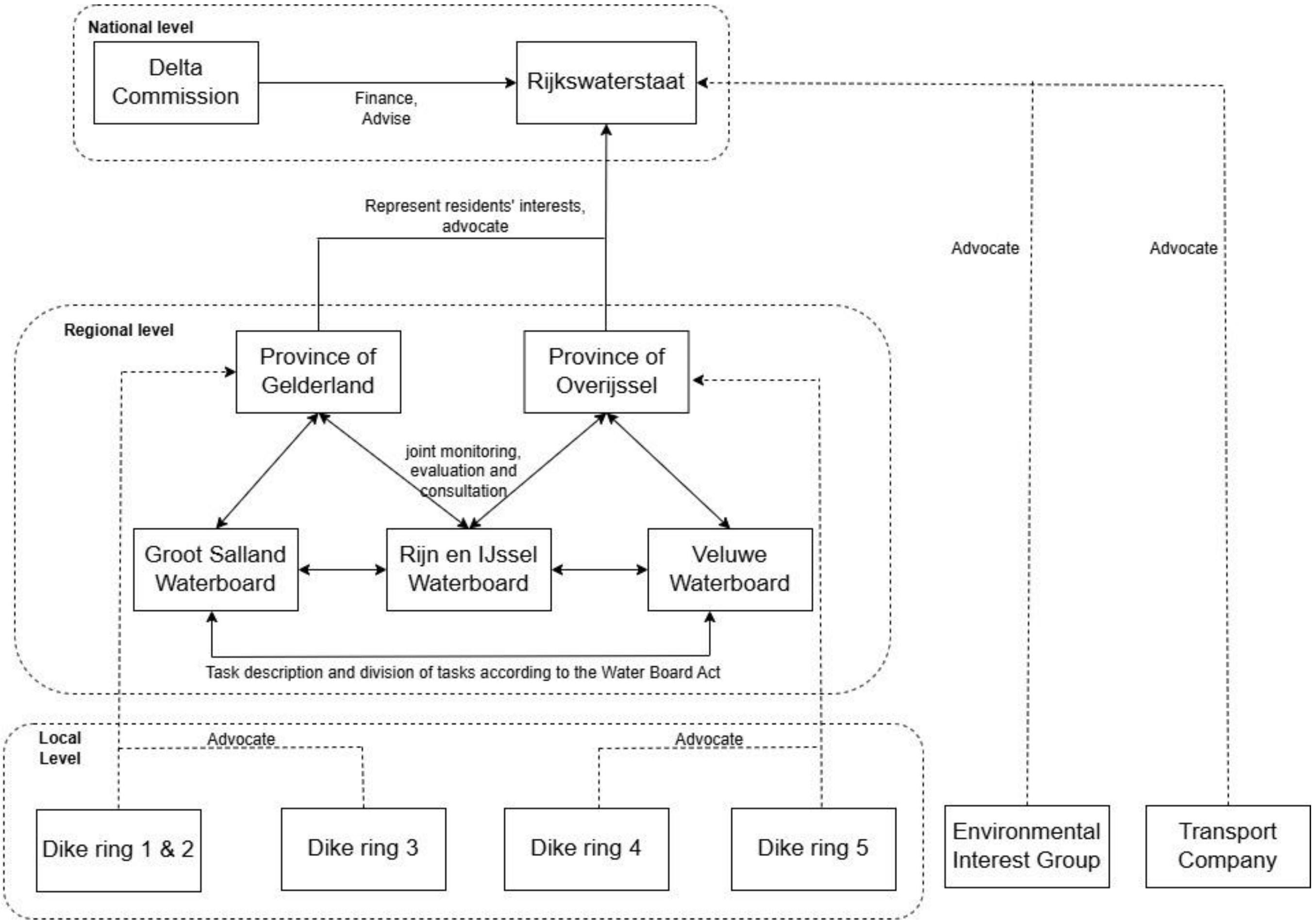

Figure A.3 - Formal Chart

National level

The figure above shows the relationships between all actors involved in the policy design for managing floods of the IJssel River. Rijkswaterstaat is tasked with drafting the final policy proposal. However, as indicated in the figure, there are many other actors who influence this policy proposal. At the national level, this includes the Delta Commission. This commission controls a budget crucial for Rijkswaterstaat to ultimately finance a policy proposal. Additionally, the Delta Commission provides advice and expresses its preferences. Rijkswaterstaat aims to align with the political vision of the Delta Commission.

Regional level

At the regional level, provinces and Waterboards are active. In managing flood risks of the IJssel River, three Waterboards are involved. These water boards adhere to the Water Board Act, which defines their tasks and distribution of responsibilities. While Waterboards operate independently from provinces, they collaborate to ensure effective regional water management. Together, they are responsible for translating national water policy into regional measures. Additionally, provinces have budgets crucial for implementing a policy proposal.

Local level

At the local level, various dike rings are active. They represent residents and farmers around specific dikes and advocate for their interests with regional actors. It is the responsibility of these regional actors to then defend these interests at the national level.

Additionally, consideration must be given to the environmental interest group and the transportation company. These actors seek to influence national-level policy by advocating for their interests and participating in debates on policy proposals.

Appendix B - political no-go's

Based on the debates, a few political no-go's emerged that the policies must meet:

Rijkswaterstaat: The primary goal is to achieve zero total deaths. Safety is of utmost importance, and any proposed policy must prioritise measures that eliminate the risk of fatalities.

Delta Commission: It is imperative to implement at least one Room for the River (RfR) project in the IJssel River. Given budget constraints, there is a strong preference for implementing two RfR projects, if feasible. Longevity and sustainability in flood risk reduction are prioritised by Delta.

Provinces: The provinces advocate for minimising costs associated with RfR projects. They are willing to contribute financially, especially if more RfR projects are undertaken, with a potential maximum contribution of up to 50% for additional projects. Their preference lies in increasing dike heights to enhance safety and minimise damage.

The environmental group and transport's group preferences will be explored but are not considered a no-go. They both stated being open for discussion about these specific wishes.

Transport: Alignment with the provinces, transport stakeholders emphasise the necessity to increase dike heights in urban areas, particularly focusing on urban dike rings 3 and 5. Their specific requirement is for these dike rings to be raised by at least 5 decimeters (dm) to ensure adequate protection against flood risks.

Environmental and Climate Change Adaptation Co-Benefits: Maximising "Room for the River" initiatives is crucial for accommodating environmental needs and adapting to climate change impacts. This stakeholder group prioritises policies that create space for natural river dynamics and environmental resilience.

Each stakeholder's preferences and constraints reflect their distinct priorities and contributions to the overall policy objectives. These requirements underscore the complexity of balancing safety, environmental sustainability, and financial considerations in flood risk management and adaptation planning.

Table B.1 - Constraints set by stakeholders

Stakeholder	**Constraint**
Rijkswaterstaat	Total deaths to zero
Delta Commission	Implementation of at least one RfR project
Provinces	Cost minimization for RfR project
Transport and Provinces	Increase in dike heightenings for safety

Environmental	Maximising room for rivers

Appendix C - Open exploration

C.1 Analysis of the Policy Space

(done on: `policy_space_refsc_256pol.tar.gz`)

Below are the results of the sensitivity analysis conducted using Sobol sampling. The first-order effects show the sensitivity of outcomes to individual policies, while second-order effects indicate the combined influence of policy interactions on outcomes. Additionally, the analysis distinguishes between sensitivities across different time steps.

Overall Deaths

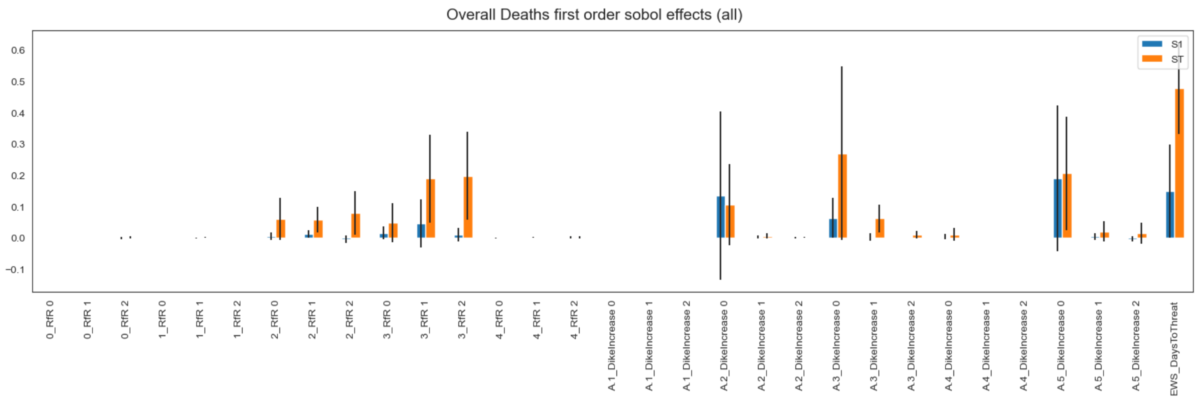

Figure C.1 - Sensitivity analysis overall deaths first order all effects

In many cases, the total effects exhibit a significant increase compared to the first-order effects, indicating the presence of second-order interactions among policy levers. Overall, the Early Warning System (EWS) in conjunction with increased dikes at areas 3 and 5, along with Room for River (RfR) projects at locations 2 and 3 across different time steps, demonstrates the highest impact on outcomes. Specifically within Room for River projects, variations in the timing of lever implementation appear to influence the overall reduction in fatalities. To delve deeper into this matter, Sobol effects are detailed for each time step:

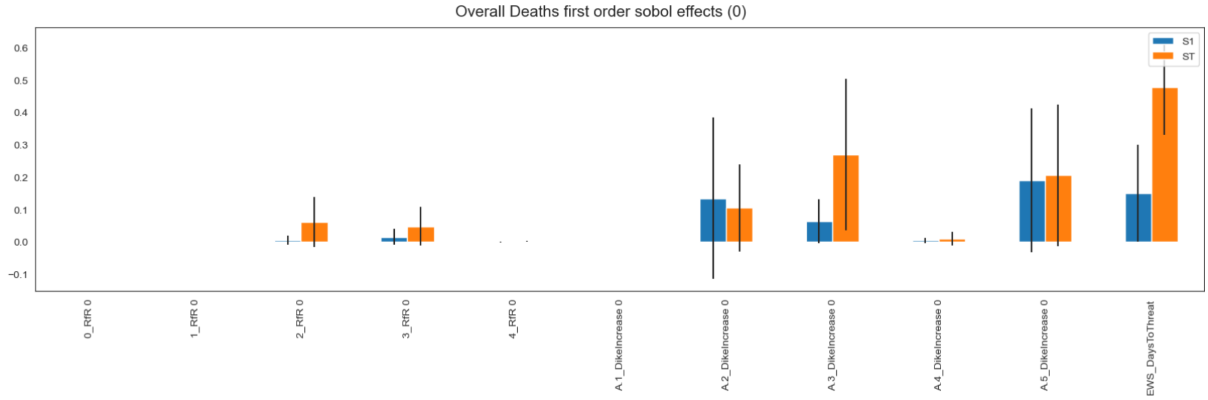

Figure C.2 - Sensitivity analysis overall deaths first order timestep 0

In the short term, the Early Warning System and dikes 3 and 5 have the biggest effect. However, in the long term we see a radical decrease in the effects of the dike heightenings and an incremental increase of the effects of room for river projects 2 and 3 on the amount of deaths.

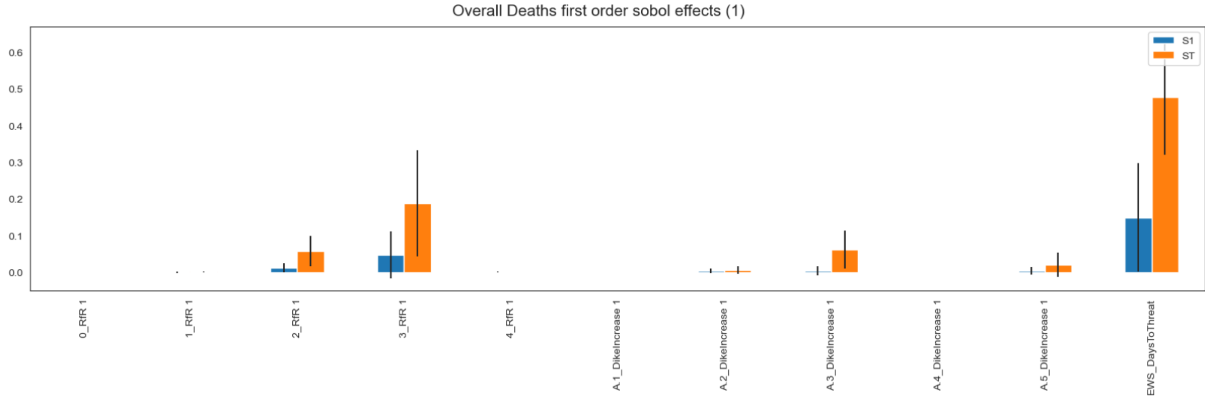

Figure C.3 - Sensitivity analysis overall deaths first order timestep 1

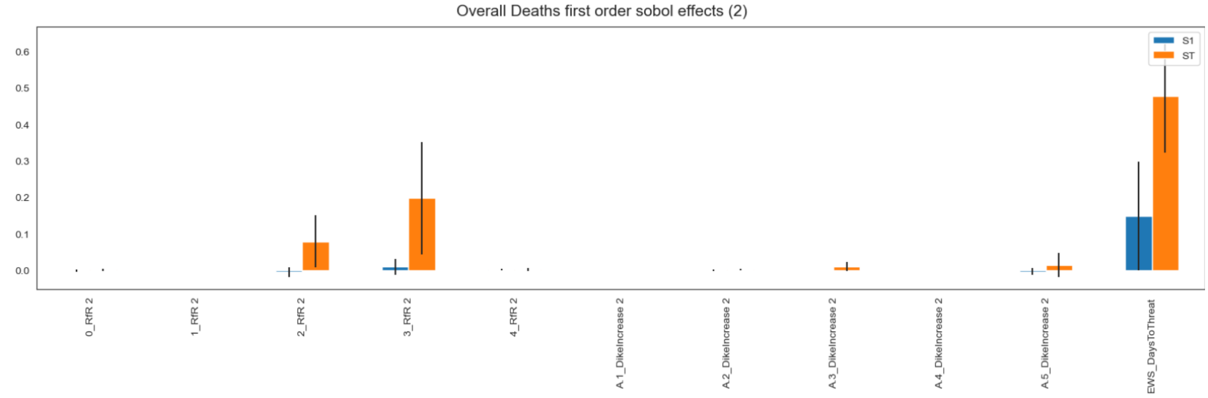

Figure C.4 - Sensitivity analysis overall deaths first order timestep 2

In the long run, the first order effects are becoming significantly less important when compared to the total order effects, implying an increase of the importance of second order effects in the long term. The second order effects that had an absolute value higher than zero are provided below.

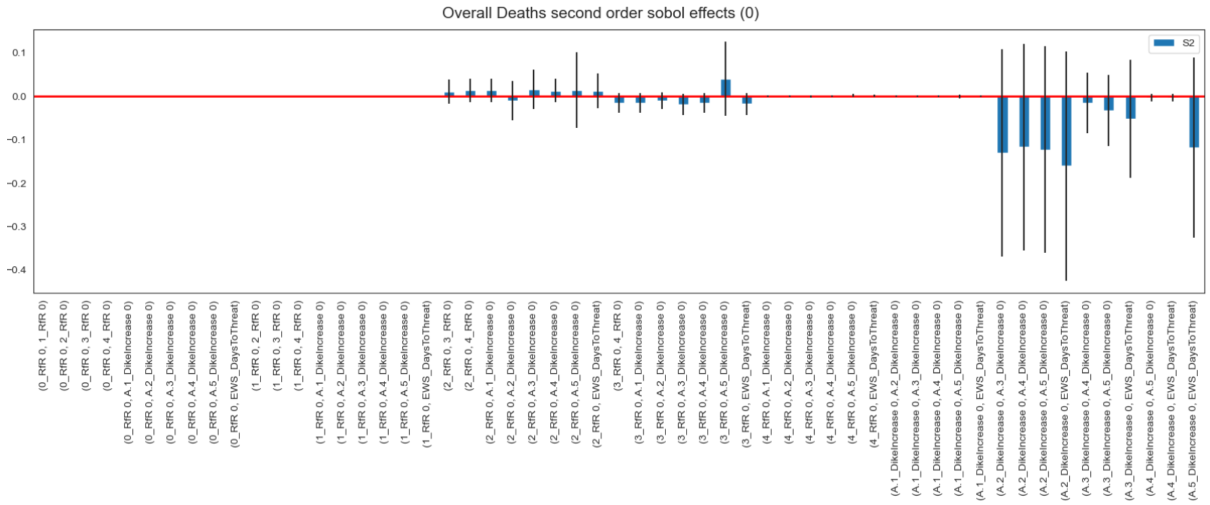

Figure C.5 - Sensitivity analysis overall deaths second order timestep 0

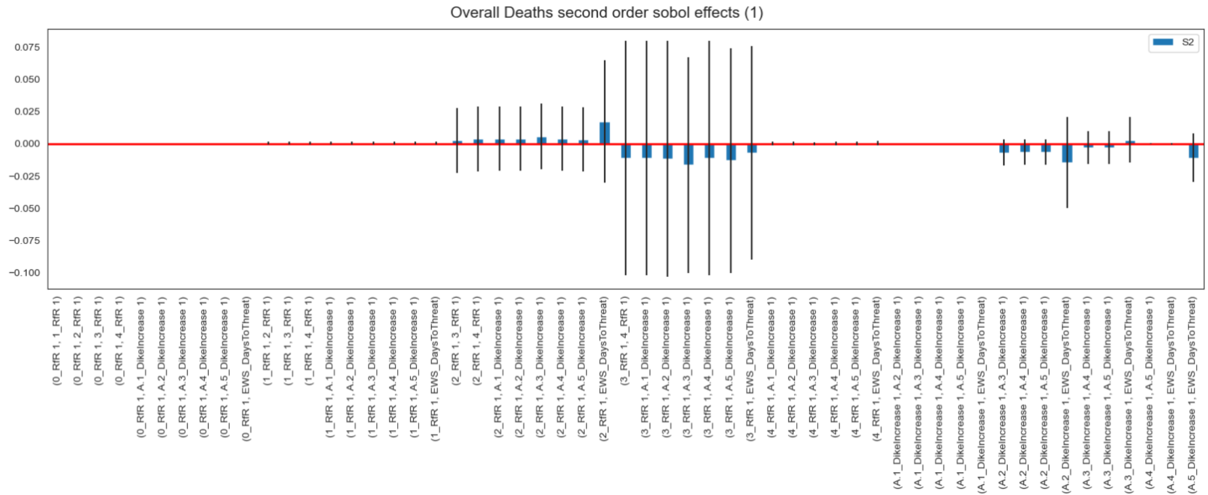

Figure C.6 - Sensitivity analysis overall deaths second order timestep 1

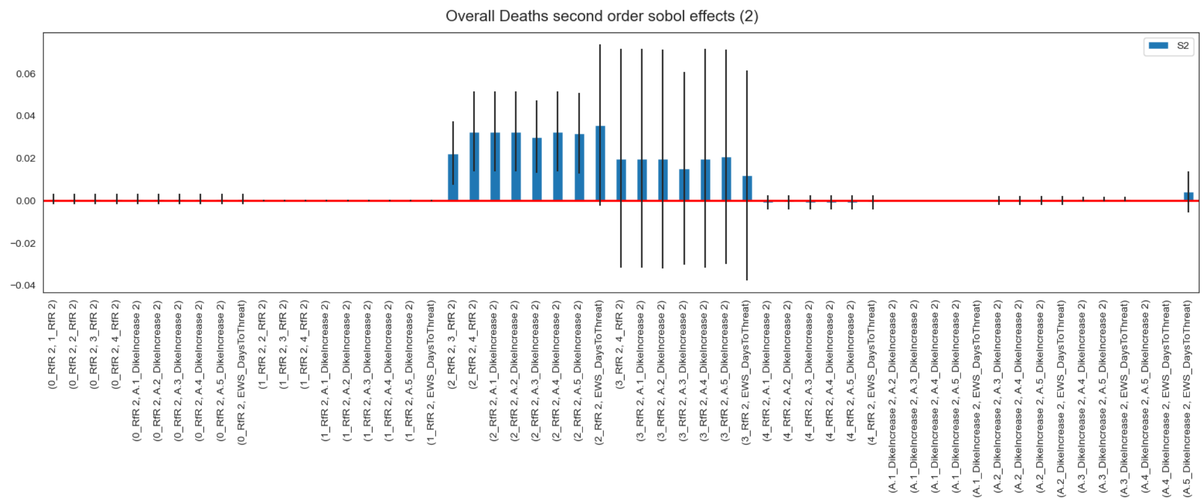

Figure C.7 - Sensitivity analysis overall deaths second order timestep 2

In the short term, dike increases combining A2 with either a dike increase at A3, A4, A5 or a EWS system have the strongest second order effect on the decrease of the total amount of deaths.

Overall Damage

Below, it is evident that initially, increasing the dike at A5 significantly reduces overall damage. However, over the long term, this effect diminishes considerably, giving way to the RfR 3 project, followed by the RfR 2 project.

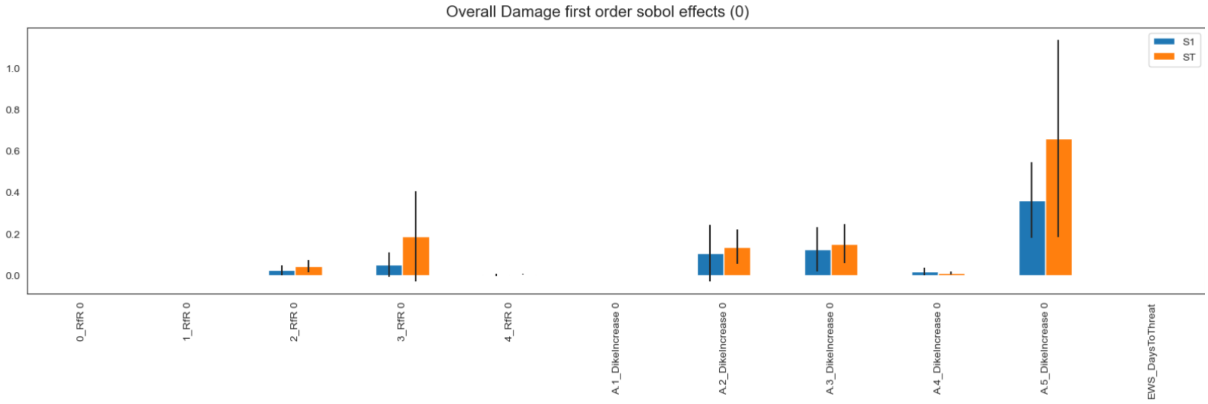

Figure C.8 - Sensitivity analysis overall damage first order timestep 0

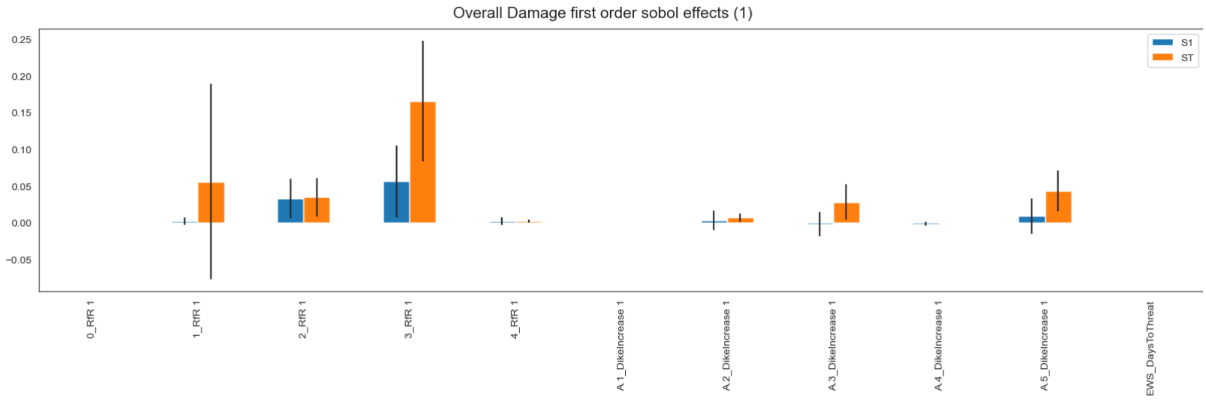

Figure C.9 - Sensitivity analysis overall damage first order timestep 1

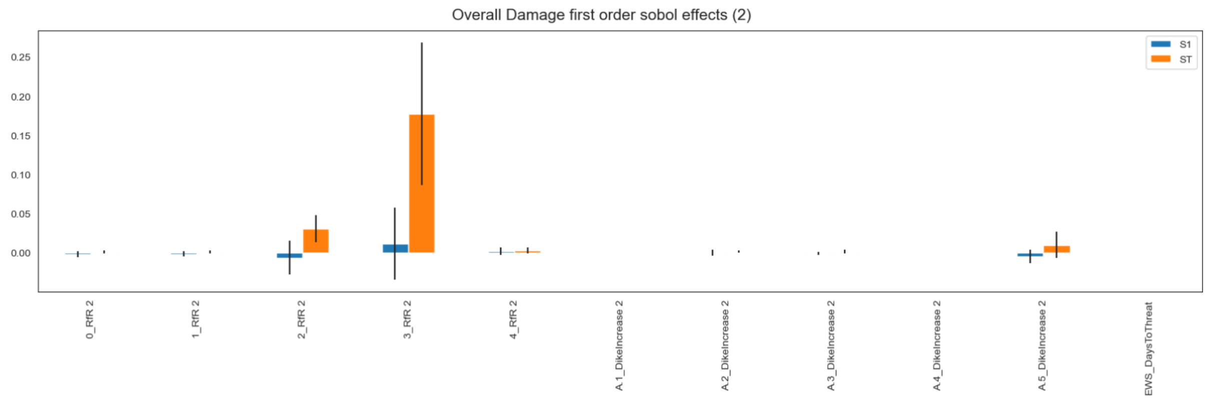

Figure C.10 - Sensitivity analysis overall damage first order timestep 2

Second order effects:

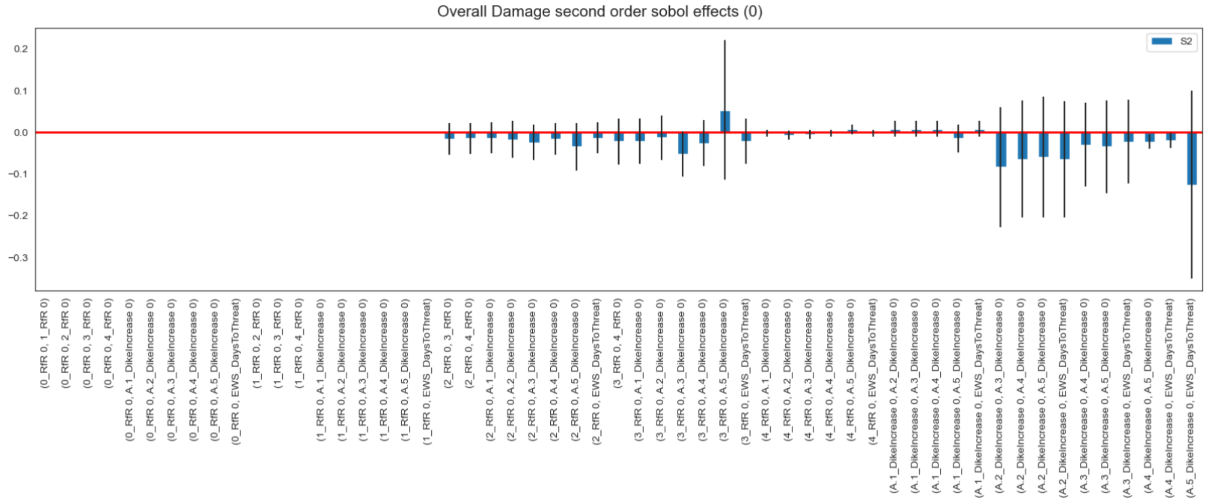

Figure C.11 - Sensitivity analysis overall damage second order timestep 0

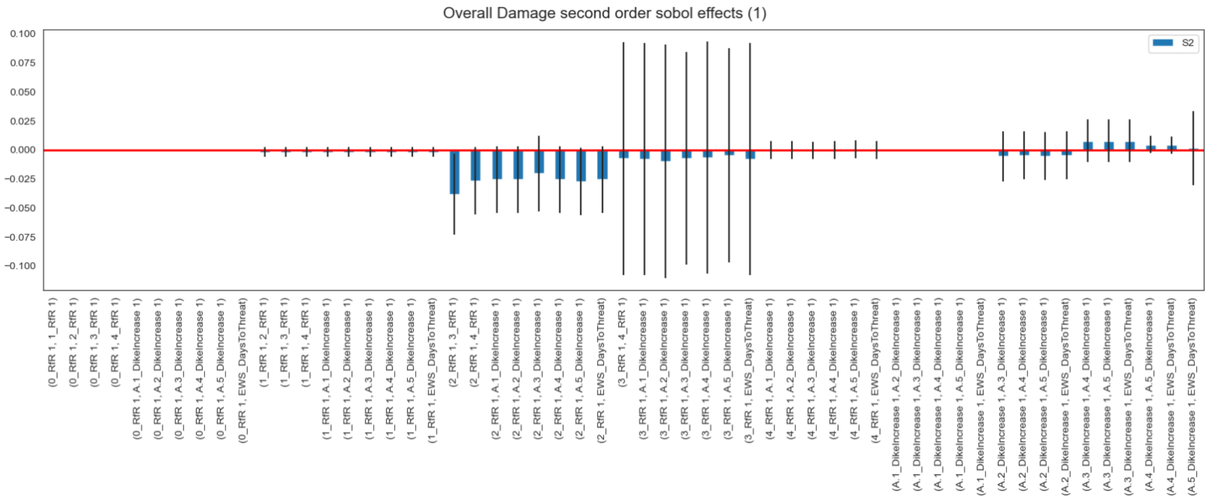

Figure C.12 - Sensitivity analysis overall damage second order timestep 1

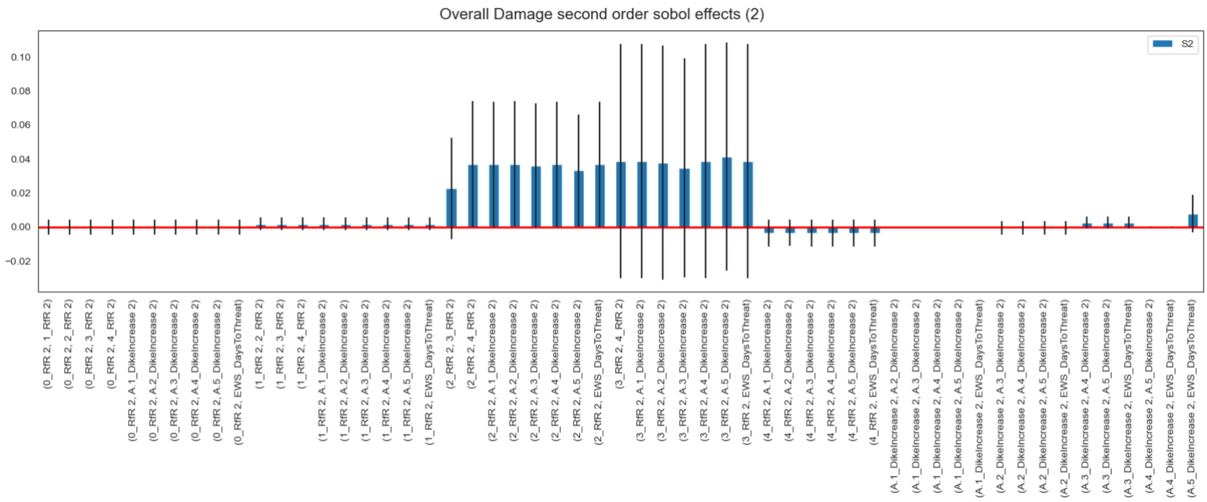

Figure C.13 - Sensitivity analysis overall damage second order timestep 2

In the long term, combinations such as the RfR 2 project with RfR 3, RfR 4, any dike increase lever, and the EWS lever, particularly those involving the RfR 3 project, appear to significantly reduce overall damage.

C.2 Feature Scoring Policy Sample

In addition to the sensitivity analysis, a feature scoring was conducted, considering both aggregated and disaggregated perspectives.

Aggregated feature scoring:

No levers seem to be scoring very high, with the highest score being 0.24.

Overall Damage is primarily affected by: A5 dike increase (0) [0.24], followed by A3 dike increase (0) [0.085].

Overall Deaths are primarily affected by the EWS days to threat [0.17] followed by early dike increases at A3 and A5 [0.10,0.11] at timestep 0.

The remaining two aggregate outcomes related to the **investment and overall costs** of the project are affected primarily by Room for the river projects, which is logical as these projects have a much higher price than other policy levers. Especially rfr 4 [0.13-0.14] and rfr 1[abt. 0.09]

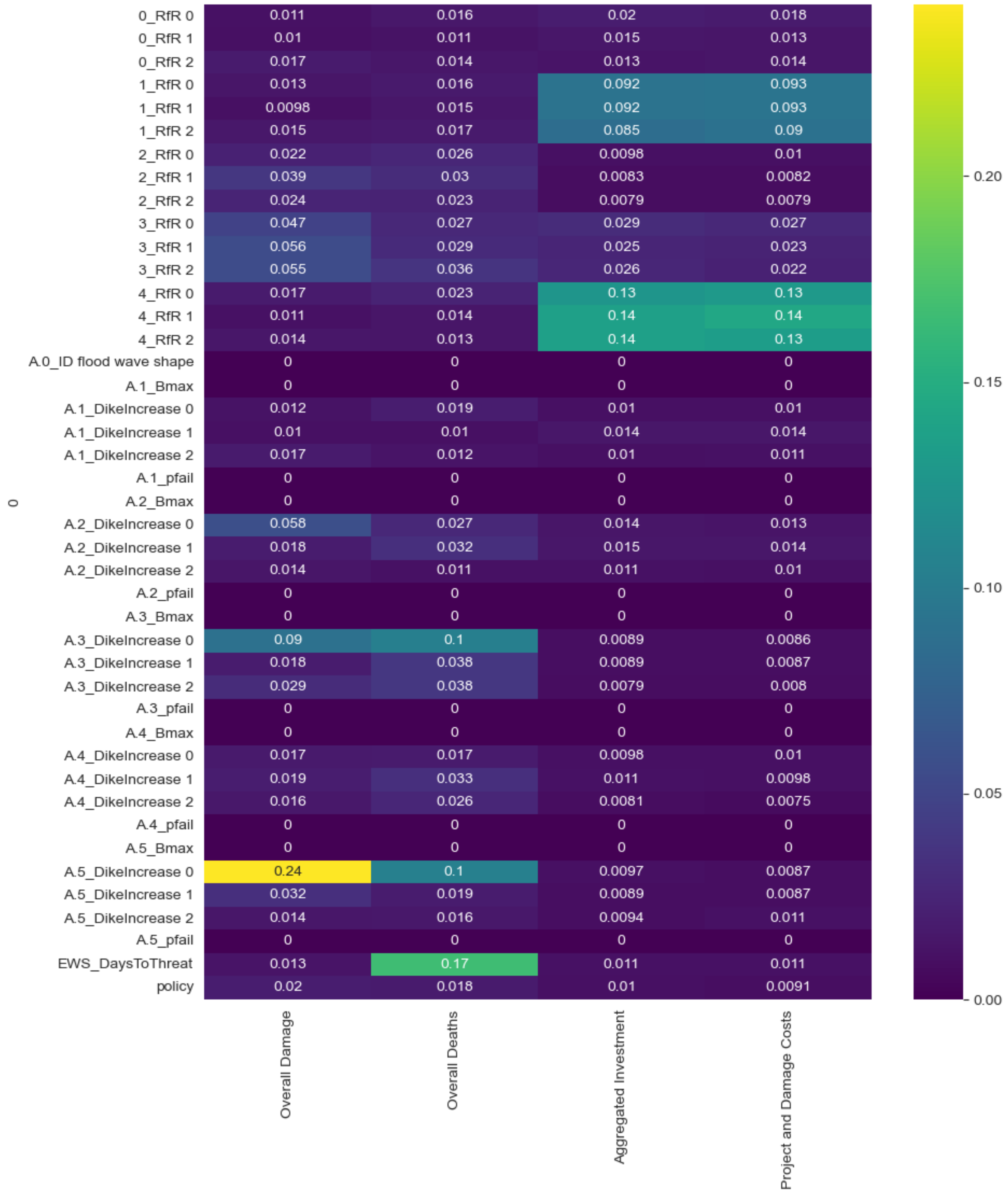

Figure C.14 - Feature scoring on policies national level

Disaggregated feature scoring:

It is crucial to examine disaggregated feature scoring to anticipate which levers will be prioritised by political bodies representing different dike-rings. Overall, the policy levers show modest scores, with the highest reaching only 0.56. However, discernible patterns emerge:

For each dike-ring, local dike heightening levers notably impact investment costs, aligning with expectations. This is logical because localised dike improvements directly affect infrastructure and property within the specific area, thereby influencing investment expenditures more significantly than broader policies.

Notably, dike heightening at specific locations during timestep 0 significantly affects expected annual damage compared to timesteps 1 or 2, underscoring the importance of early dike improvements. Early interventions in dike heightening can mitigate risks earlier, reducing potential damage over the long term. This timing sensitivity highlights the strategic advantage of prioritising initial actions for effective risk management.

Moreover, the Early Warning System's days to threat and dike heightening at A5 during timestep 0 exert considerable influence on evacuation costs. The EWS's capability to provide timely alerts and the immediate reinforcement of critical infrastructure like dike A5 early in the scenario preparation phase directly impacts evacuation logistics and costs. The EWS, in particular, plays a critical role in enhancing response efficiency and minimising casualties across different dike-rings (excluding the first), highlighting its pivotal role in disaster preparedness and response planning.

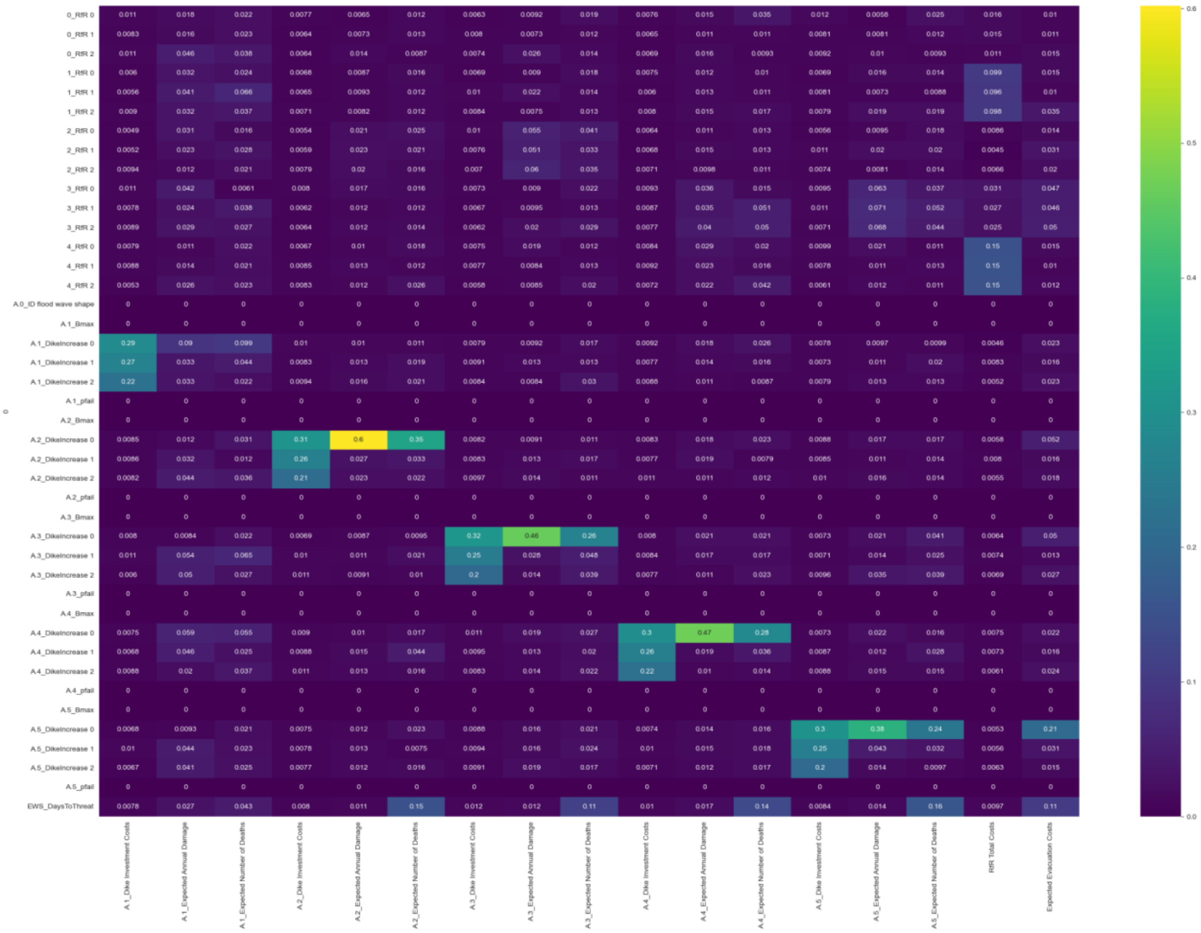

Figure C.15 - Feature scoring on policies regional level

C.3 Analysis of the Uncertainty Space

(done on: `uncertainty_space_1024sc_refpol.tar.gz`)

Presented below are the results from the sensitivity analysis conducted with Sobol sampling. The first-order effects highlight how outcomes are sensitive to individual uncertainties, while second-order effects reveal the collective impact of interactions among these uncertainties on outcomes. The analysis does not account for differences in time steps, as the discount rate is the only factor per timestep, and its influence is minimal.

Overall deaths

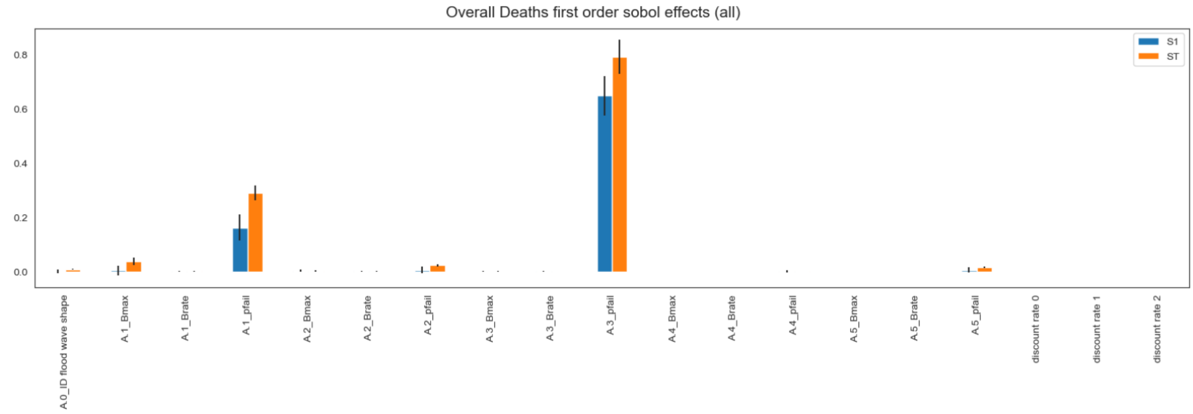

Figure C.16 - Sensitivity analysis overall deaths first order all effects

We see that A.1_pfail and A.3_pfail are the two dominant parameters to which the model is sensitive when we look at the overall deaths as outcome.

When we look at the second order effect of the overall deaths we can see that by combining A.1 and A.3 you get the biggest effect in the model.

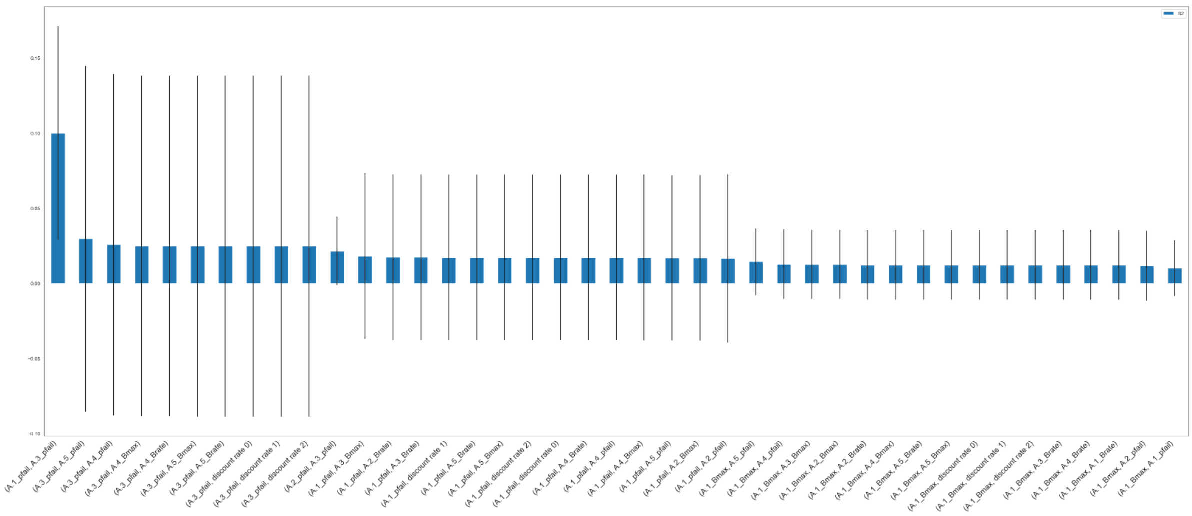

Figure C.17 - Sensitivity analysis overall deaths second order all effects

Overall damages

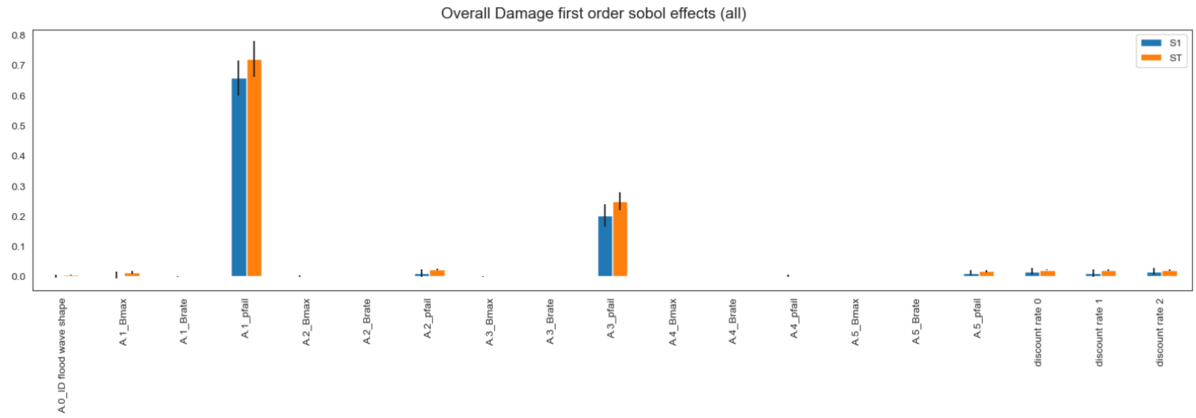

Figure C.18 - Sensitivity analysis overall damage first order all effects

Again A.1_pfail and A.3_pfail have the biggest effect to which the model is most sensitive when we look at the overall damages as outcome. The same conclusions can be drawn here. Looking at the second order again gives the biggest effect when you combine the two factors.

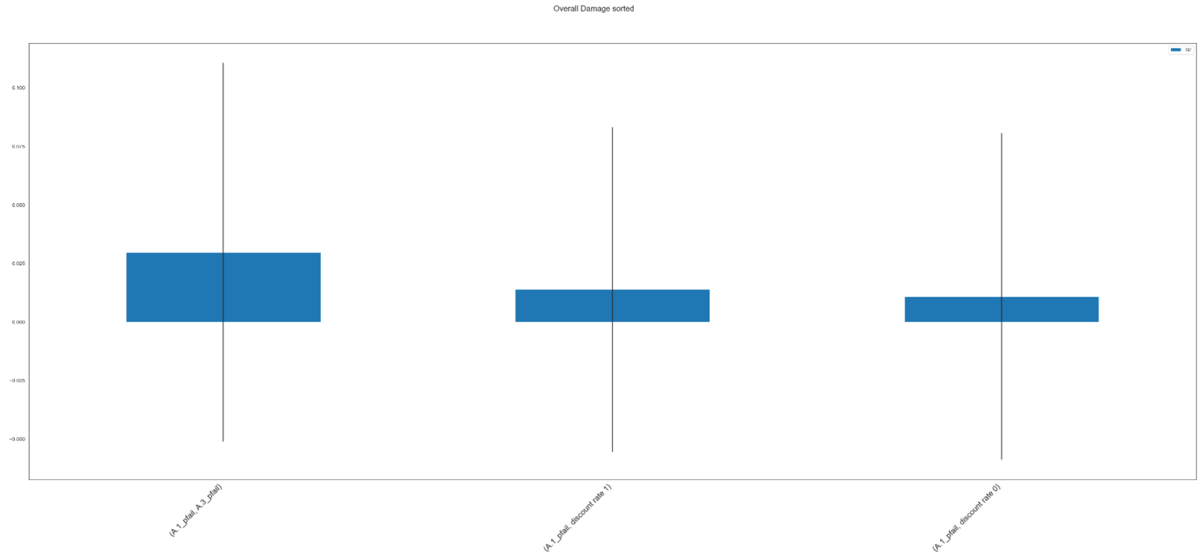

Figure C.19 - Sensitivity analysis overall damage second order all effects

C.4 Feature Scoring Uncertainty Sample

In addition to the sensitivity analysis, a feature scoring was conducted, considering both aggregated and disaggregated perspectives.

Aggregated feature scoring:

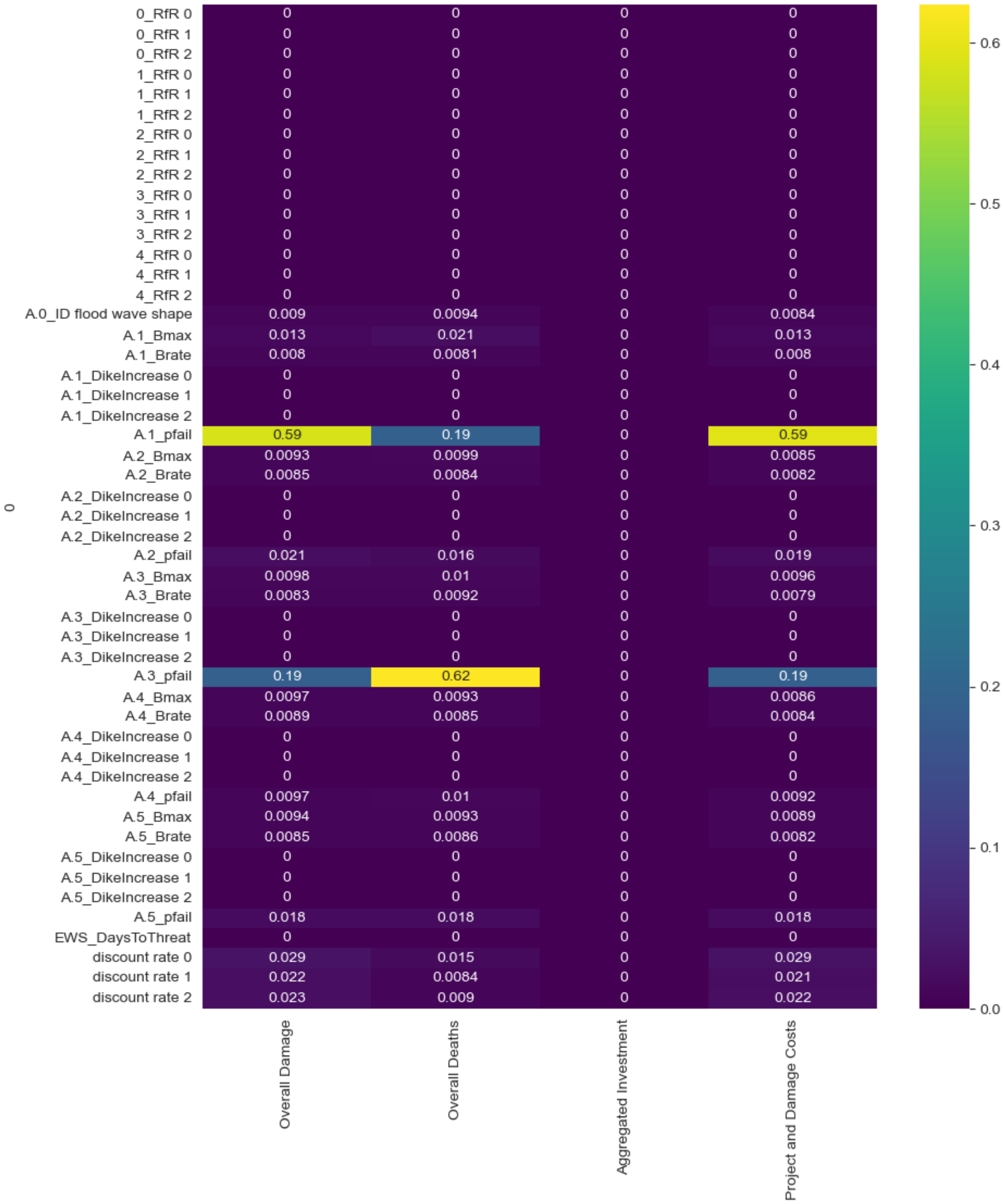

Figure C.20 - Feature scoring on uncertainties national level

On a national level you can see that A.1_pfail and A.3_pfail have the most influence on the outcomes.

Disaggregated feature scoring:

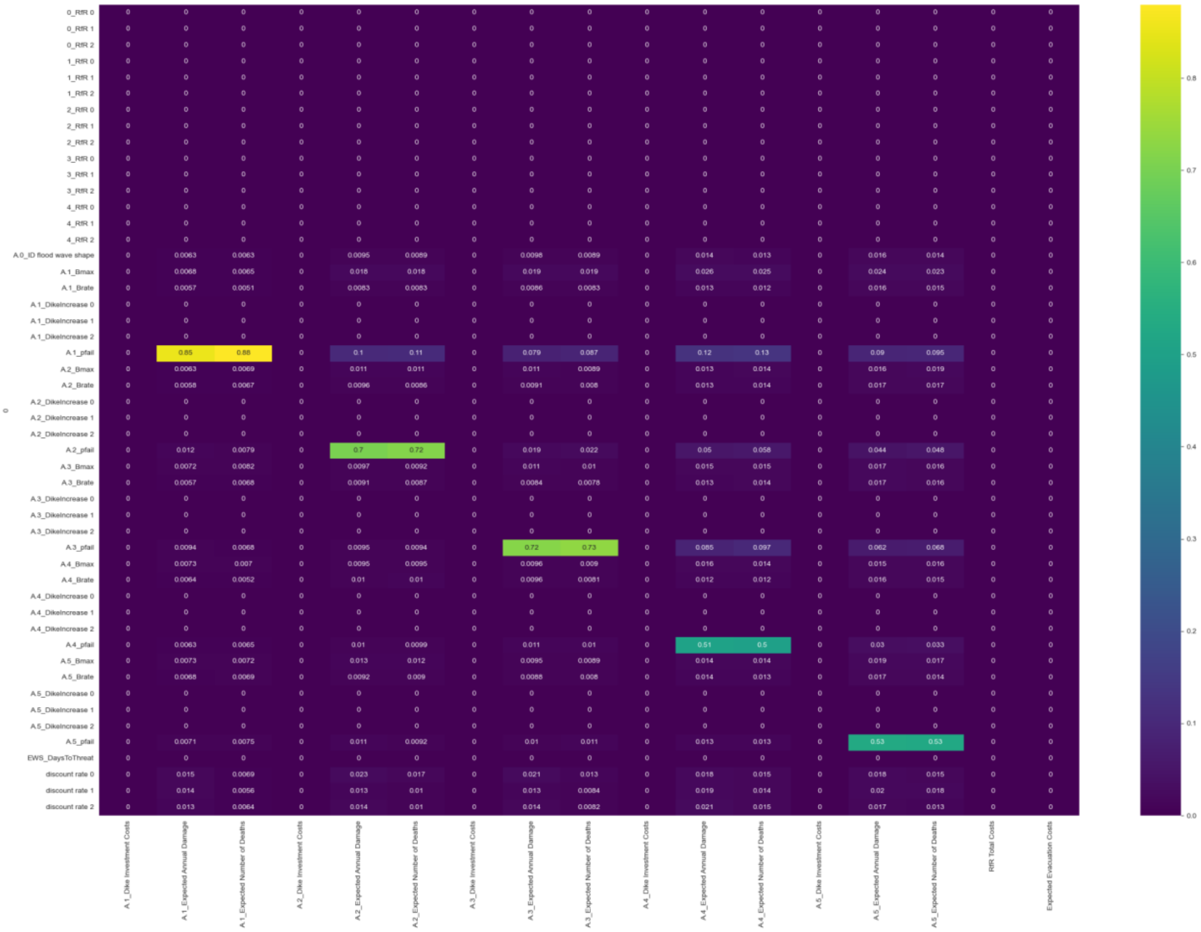

Figure C.21 - Feature scoring on uncertainties regional level

On a regional level it shows that all the pfails have an influence on the expected annual damage and expected number of deaths per location. The uncertainty has a higher influence at the first 3 locations.

Appendix D - Scenario discovery

These are the results of the 2 outcomes of the PRIM coverage and density tradeoffs. Both outcomes show the worst 20% in the trade offs.

Overall deaths

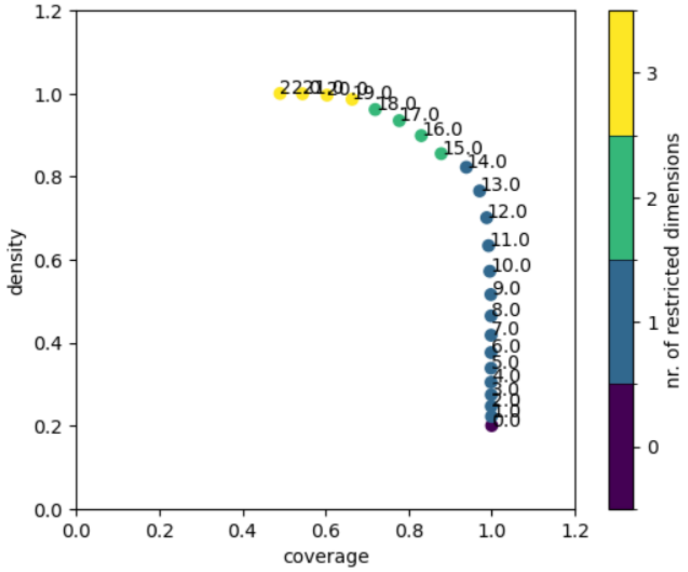

Figure D.1 - PRIM analysis on overall deaths

Expected annual damage

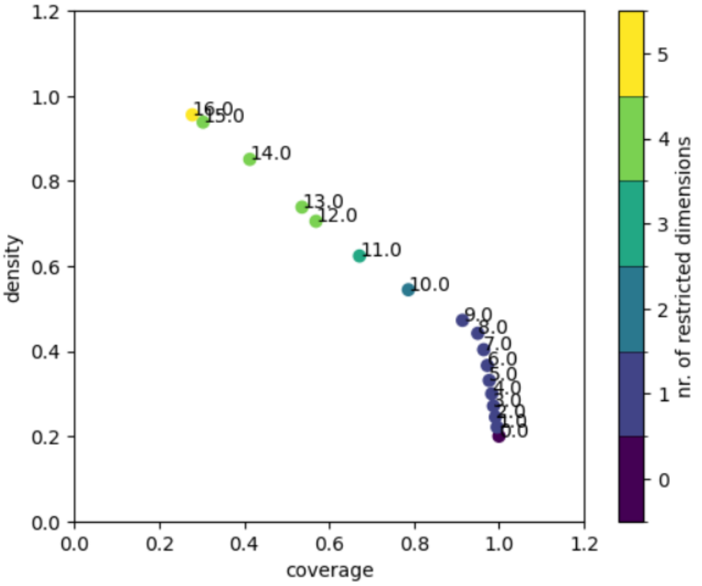

Figure D.2 - PRIM analysis on expected annual damages

Appendix E - Robustness assessment

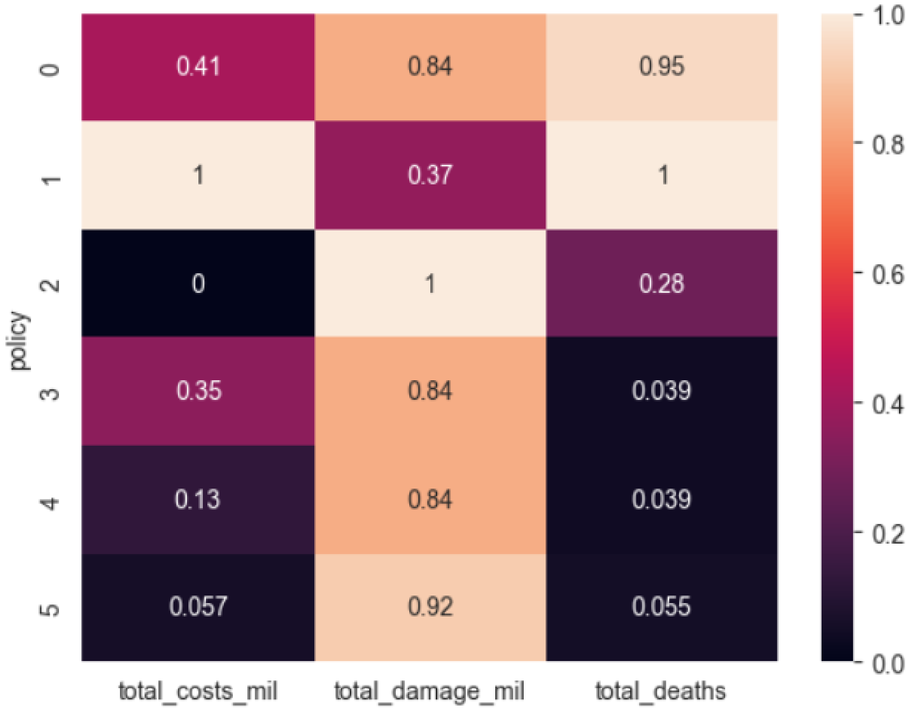

Figure E.1 : Maximum-regret heatmap of the aggregate results

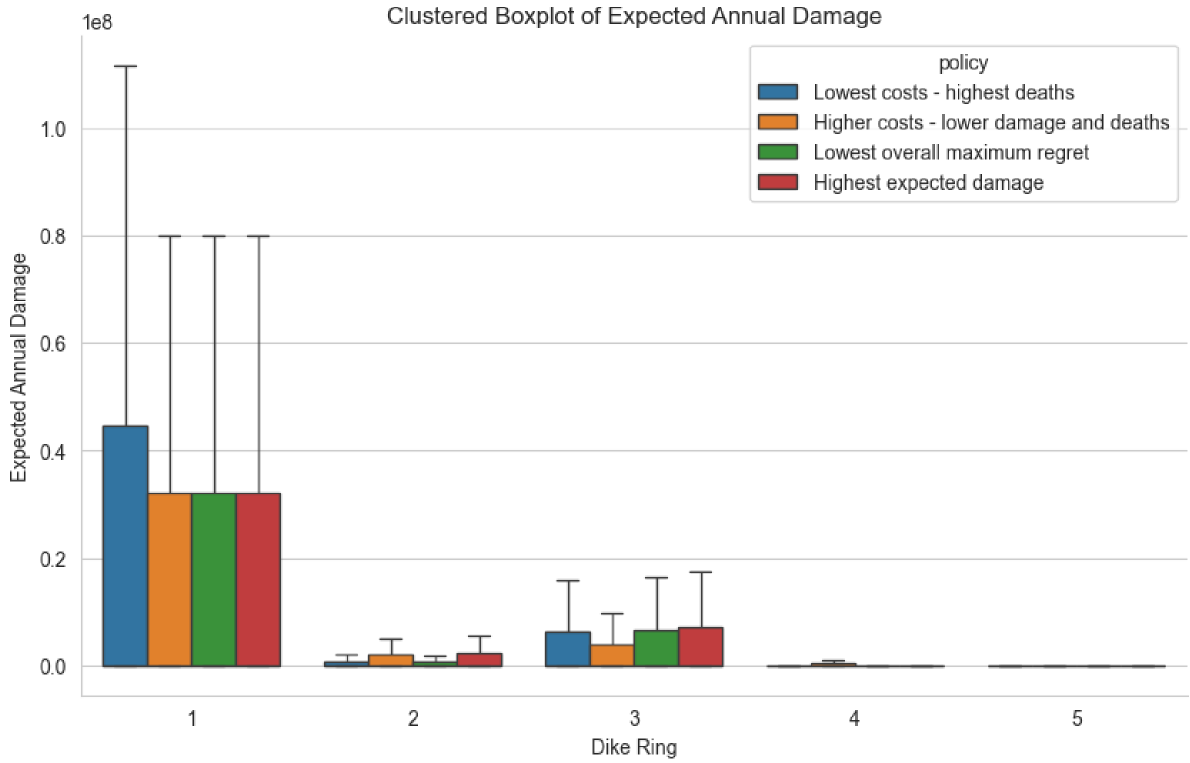

Figure E.2 : Distribution of Expected Annual Damage over the Dikerings

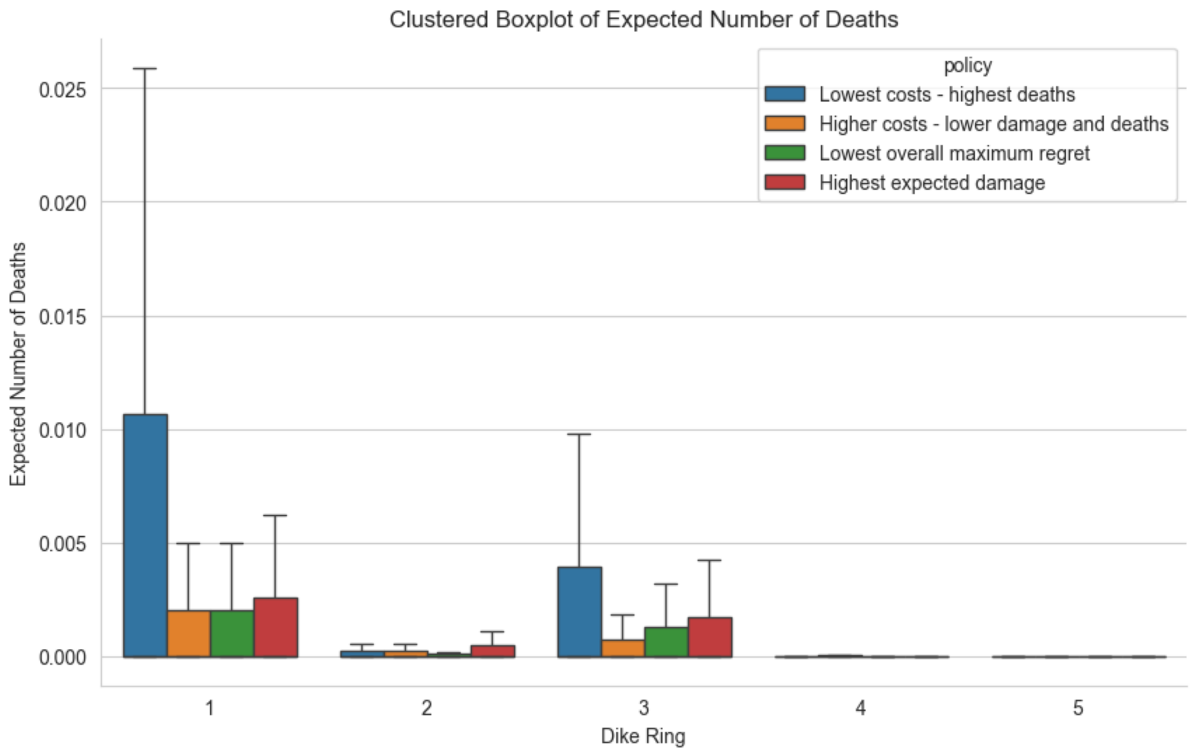

Figure E.3: Distribution of Expected Annual Damage over the Dikerings